Top Jets & Boosted QCD Jets @ the LHC

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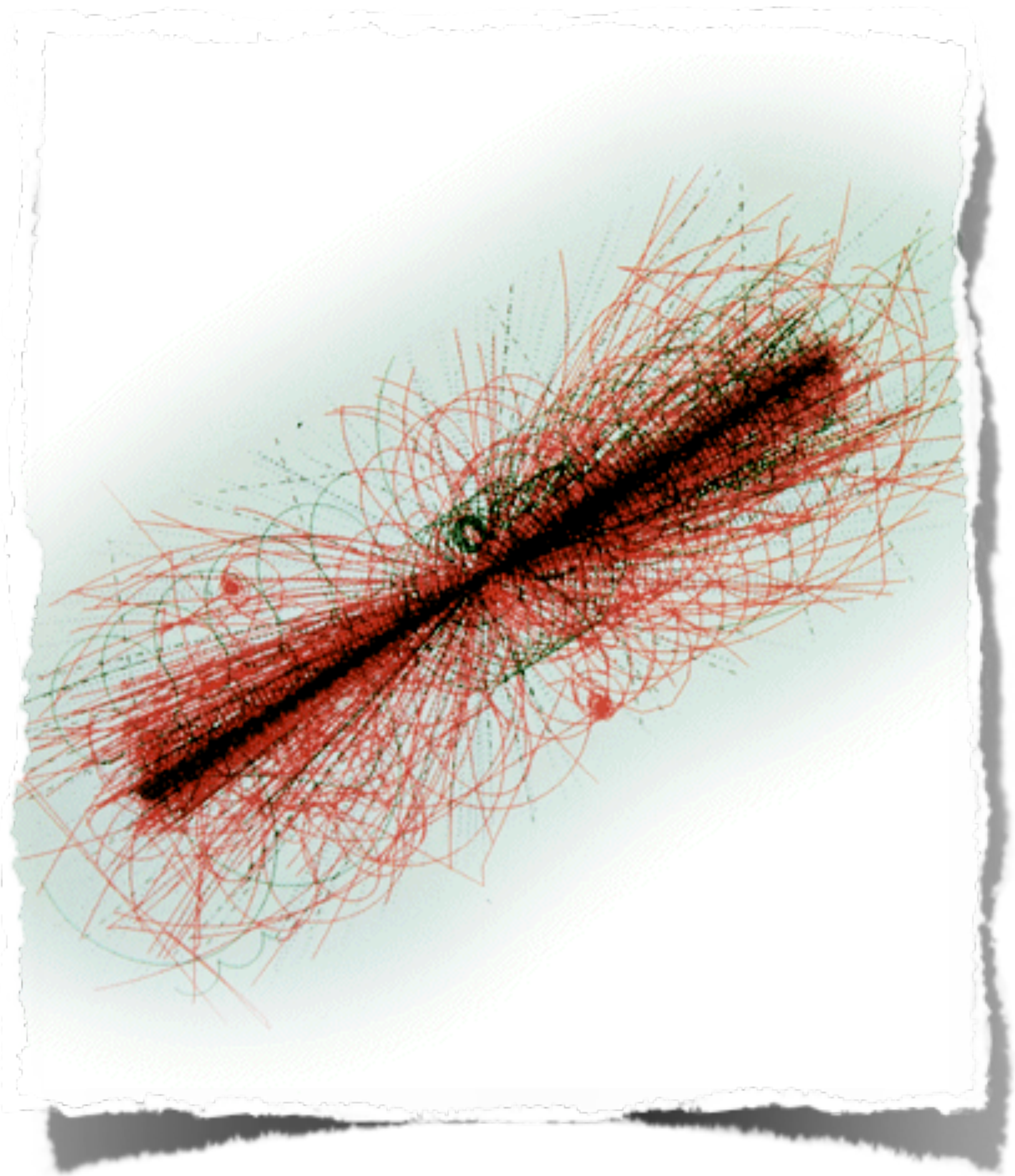
with L. Almeida, G. Perez, G. Sterman, I. Sung, J. Virzi (x2)
with G. Perez, J. Virzi

arXiv:0807.0234, work in preparation

Santa Fe 2008 Summer Workshop

Outline

- ✦ Introduction
- ✦ Emergence of top (W,Z,h) jets at the LHC
- ✦ Jet mass: Signal & QCD BG (theory+MC)
- ✦ Jet substructure, massive jet event shapes
- ✦ (top polarization)
- ✦ Summary



Introduction

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  only ultra heavy quark, $m_t \sim \langle H \rangle$
  induce most severe fine tuning;
  controls flavor & custodial violation;
  linked to EW breaking in natural models.

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  only ultra heavy quark, $m_t \sim \langle H \rangle$
  induce most severe fine tuning;
  controls flavor & custodial violation;
  linked to EW breaking in natural models.
- Direct info' is limited (Tevatron)
- At the LHC: 10^7 top/yr
- SM: more than 10^4 top/yr with $\gamma_t \geq 5.$

Efficiencies & tagging \w boosted tops

- The hadronic calorimeters cannot go below R~0.4

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Hadronic granularity is R~ 0.1 x 0.1

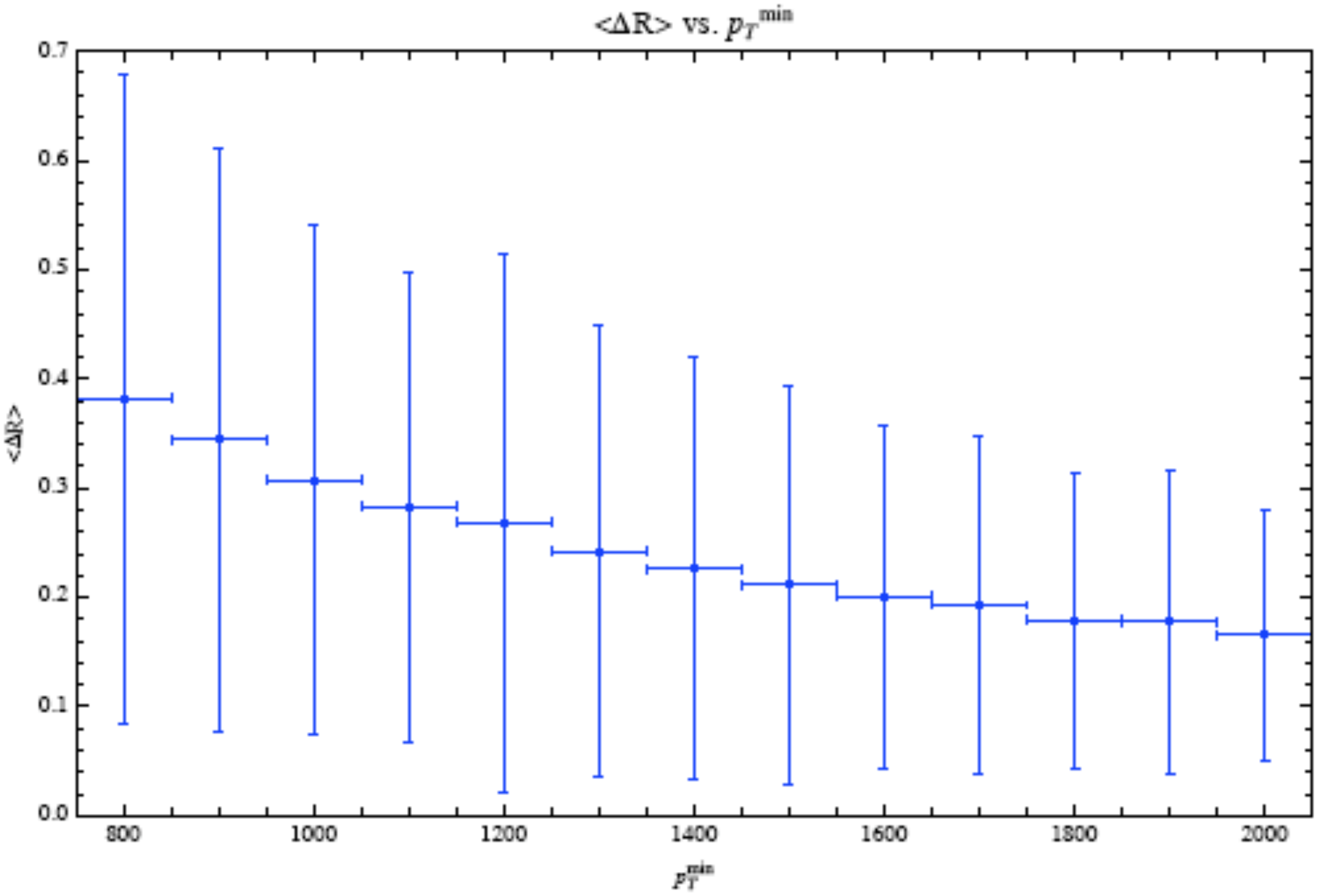
$$m^2 = (p_1 + p_2)^2 \sim 2p^2[1 - (1 - R^2/2)] = p^2\, R^2$$

$$\text{pure geometrical mass:} \quad m \sim R\,p$$

$$(\text{say with } R, p = 0.2, 500\,,\ m \sim 100\text{GeV})$$

Boosted top (w/z/h) jets & collimation

Almeida, SJL, Perez, Sterman, Sung & Virzi, to appear.

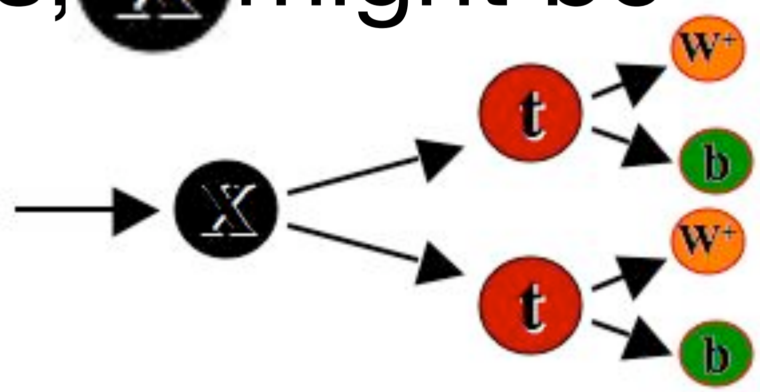


Highly Boosted Tops:
High Collimations!

ΔR vs. P_T

The challenge of highly boosted tops

- No deviation in indirect searches,  might be heavy.



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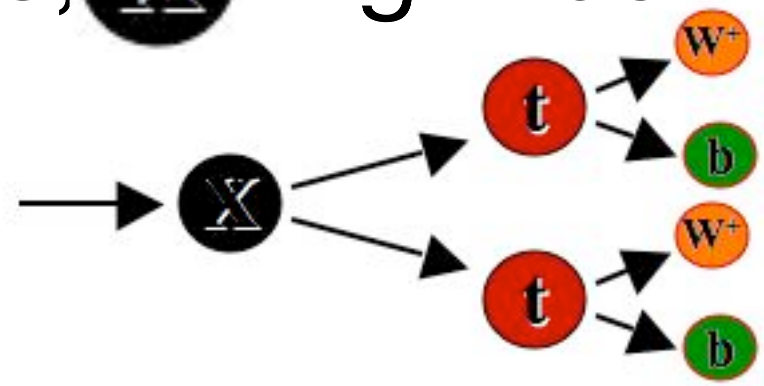
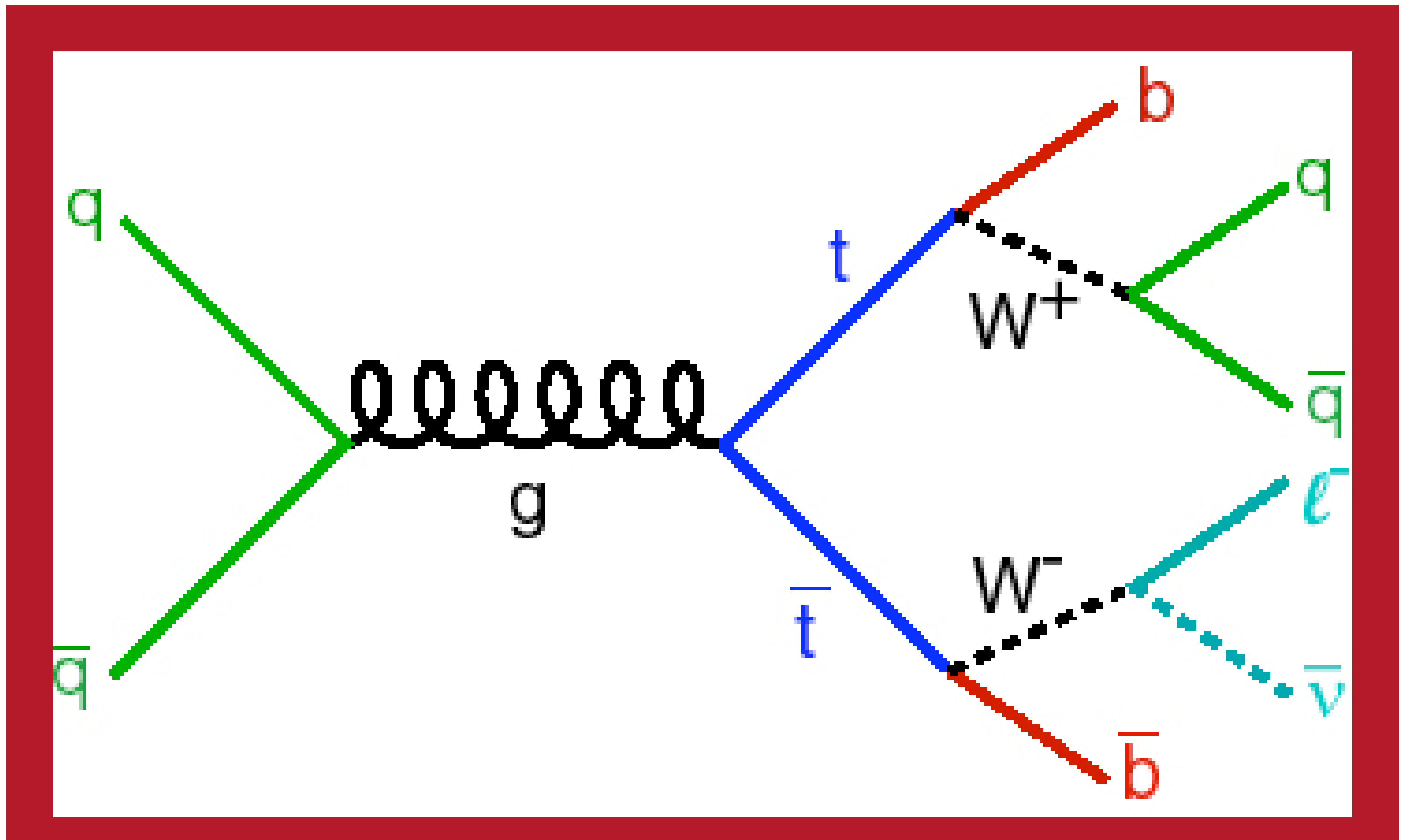


- Alas, above a TeV, top becomes similar to a light jet, signal is **lost**!



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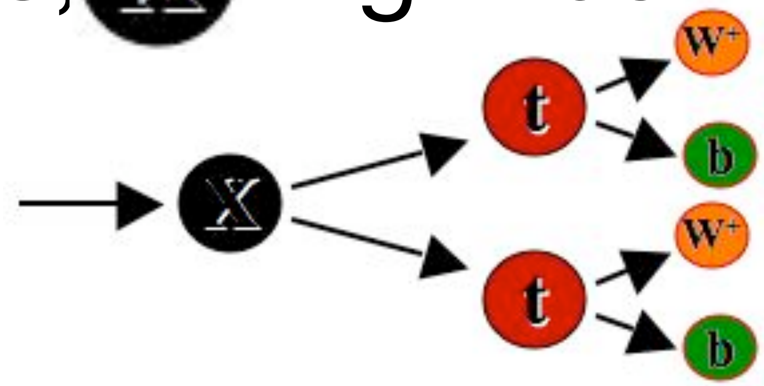

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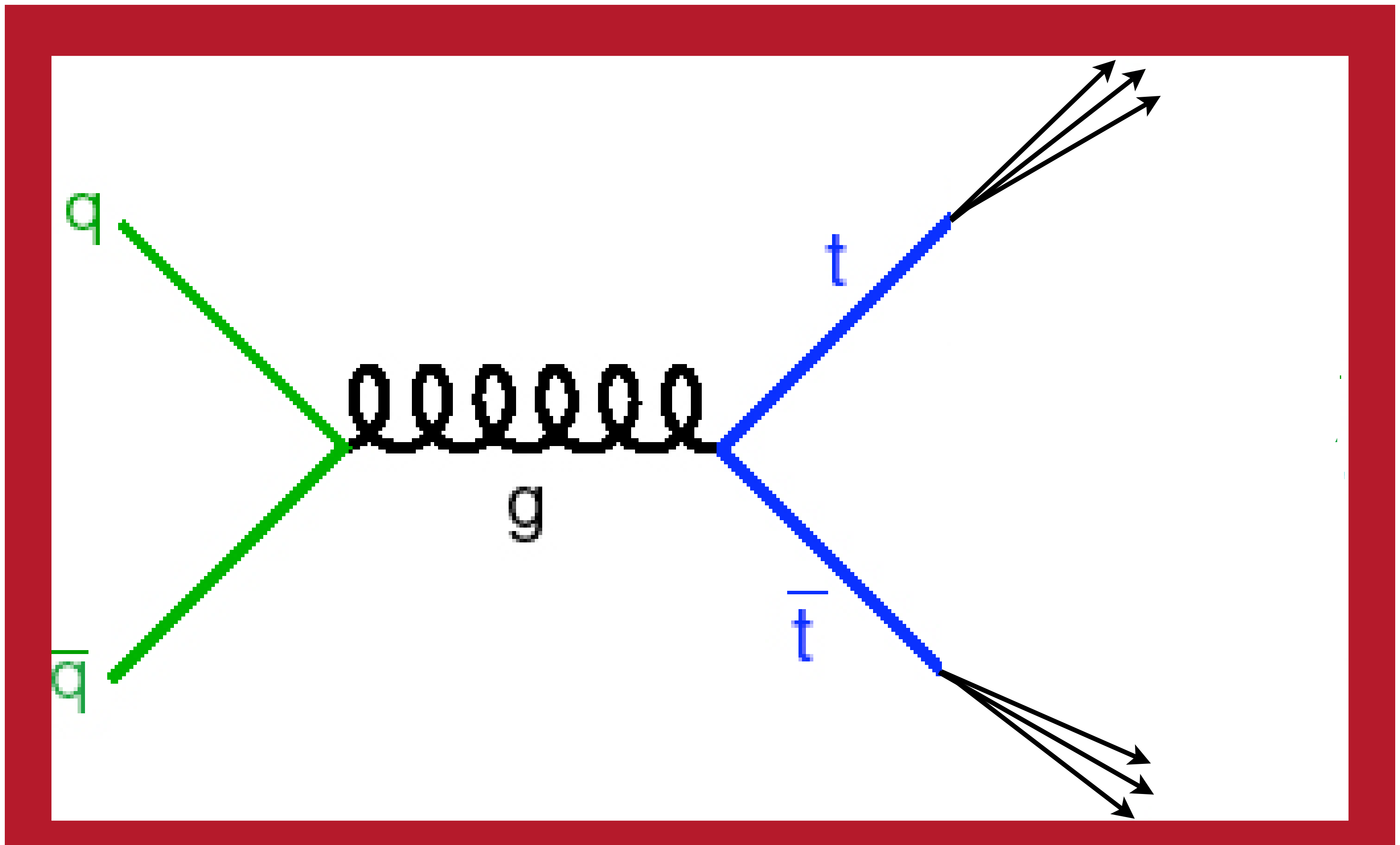

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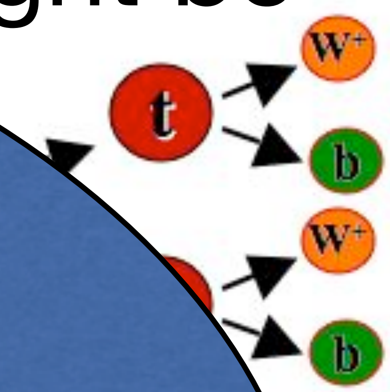
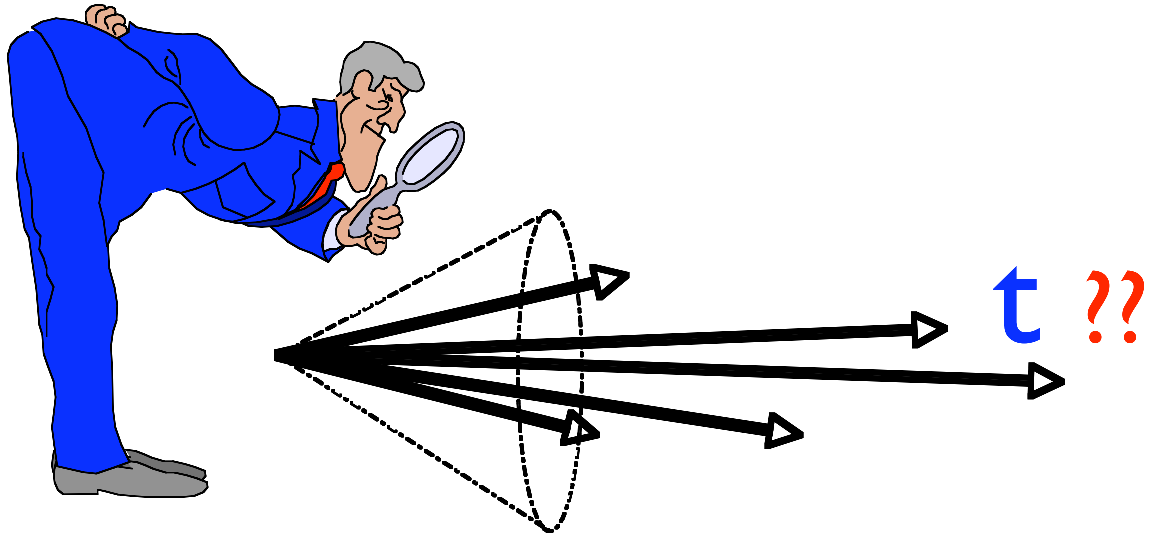


...ght

New object emerges, top jet!

Look for alternative top-tagging

- Hadronic-Leptonic tops: assume it's a top via its decay products $b + \mu + \bar{\nu}_\mu$ (missing E) & reject backgrounds. *Agashe, Belyaev, Krupovnickas, Perez & Virzi, PRD (06); Baur & Orr, PRD (07,08); Thaler & Wang* 0806.0023, SJL, Perez & Virzi, to appear; Bai & Han (di-leptonic)



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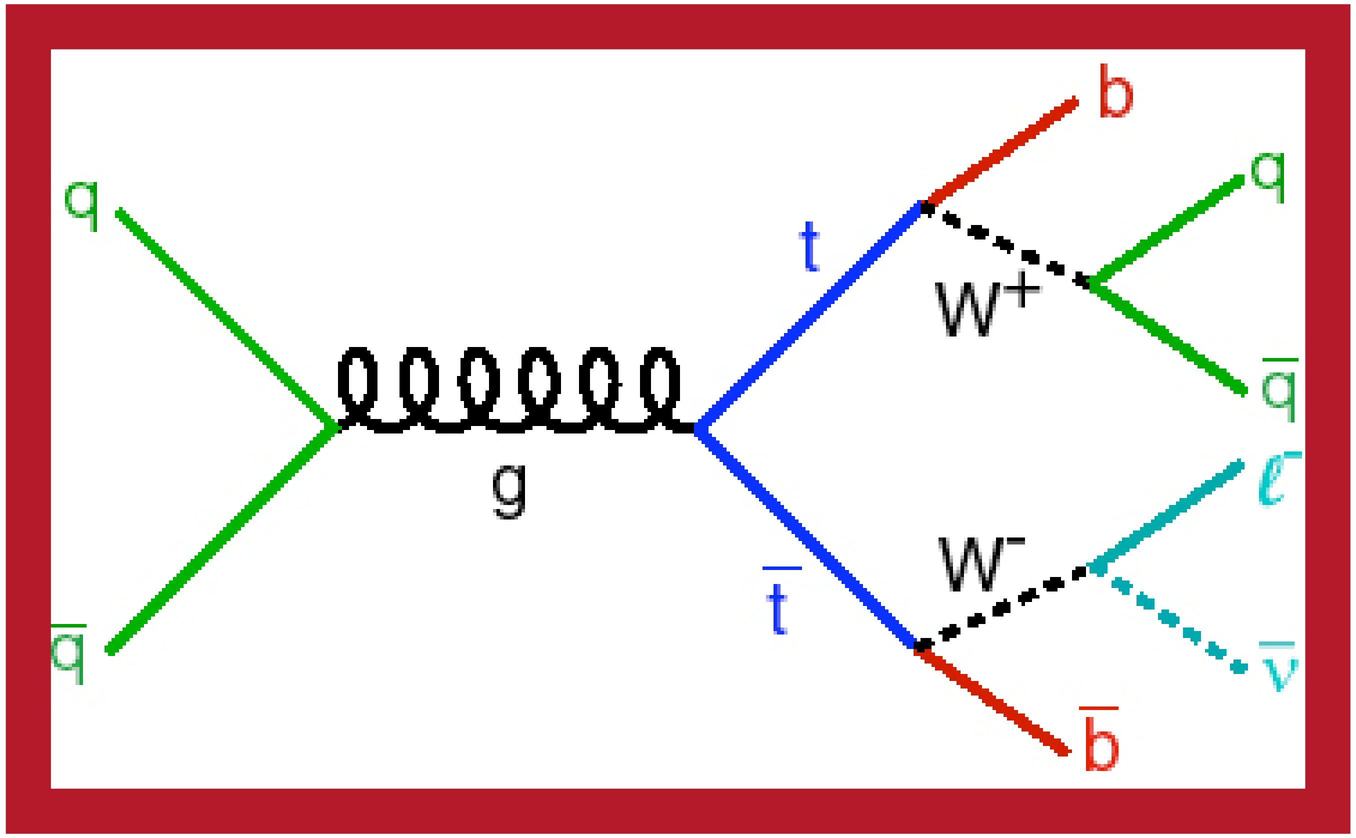

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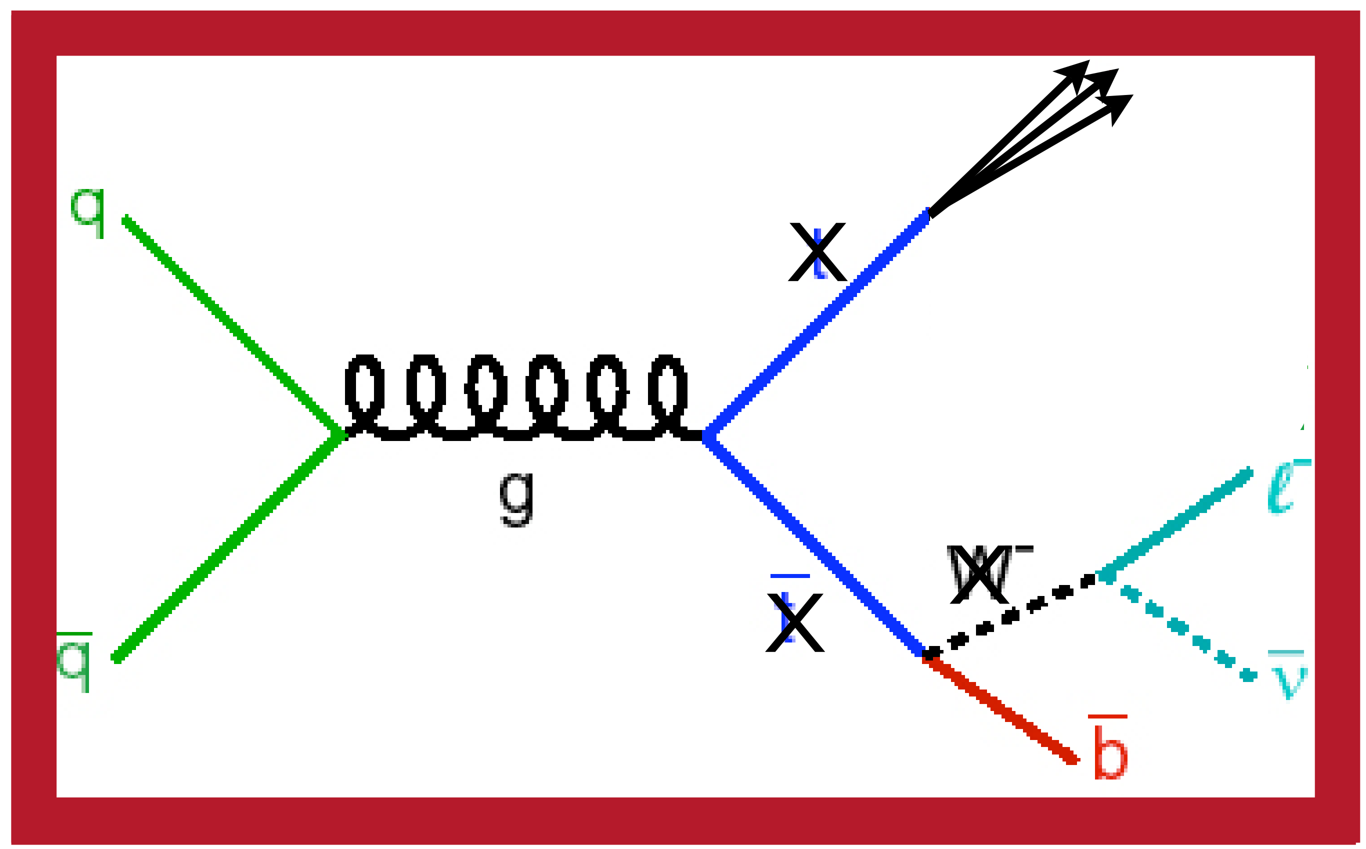
gave up on
the hadronic top?



Give-up on hadronic tops??

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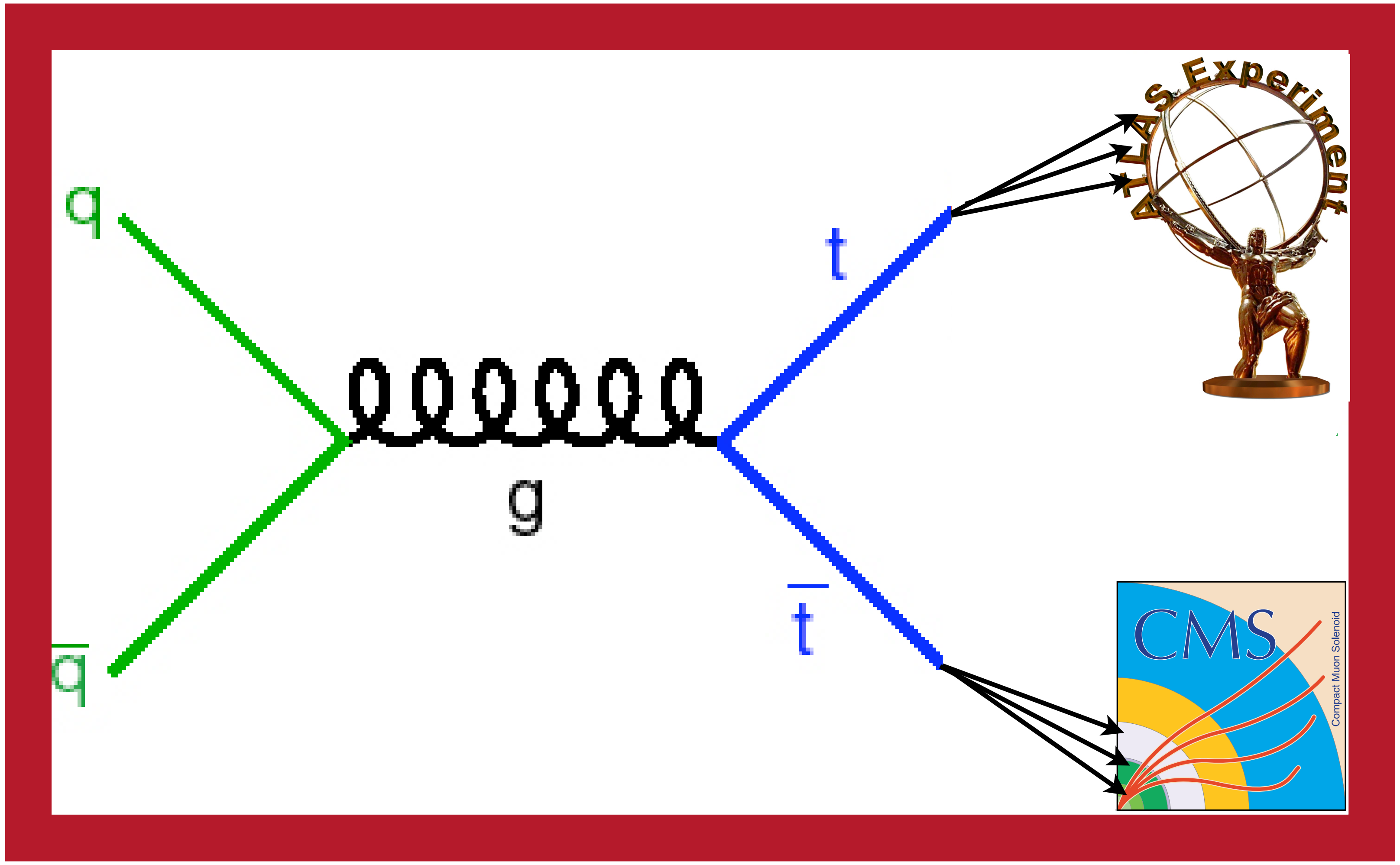
Top jets at the LHC



(i) Jet mass.

(ii) Jet substructure.

Top-jets @ the LHC

- Are they different from high p_T light jets?

  S/B~1/300, for $p_T(j)$ >1000 GeV, R=0.4

  (40 pb for jj+X, 140 fb for ttbar+X)

- top-jet: call for theory, analysis & techniques

  Most (naive) direct attempt - mass tagging

Skiba &Tucker-Smith, PRD(07); Holdom, JHEP (07); Frederix & Maltoni (0712.2355)*; Ellis, Huston, Hatakeyama, Loch & Tonnesmann, PPNP (08); Agashe et. al. PRD(07).*

Rejection based on jet mass

- Jet cone mass-sum of "massless" momenta in h-cal inside the cone: $m_J^2 = (\sum_{i \in R} P_i)^2$, $P_i^2 = 0$

- Jet cone mass is non-trivial both for S & B

- Understand S&B distributions from 1st principles & compare to MC "data"

- Add detector effects

Cone top-jet mass distribution

- Naively the signal is $J \propto \delta(m_J - m_t)$
- In practice: $m_J^t \sim m_t + \delta m_{QCD} + \delta m_{EW}$

  + detector smearing.

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Can understood perturbatively fast & small~10GeV

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perturbatively
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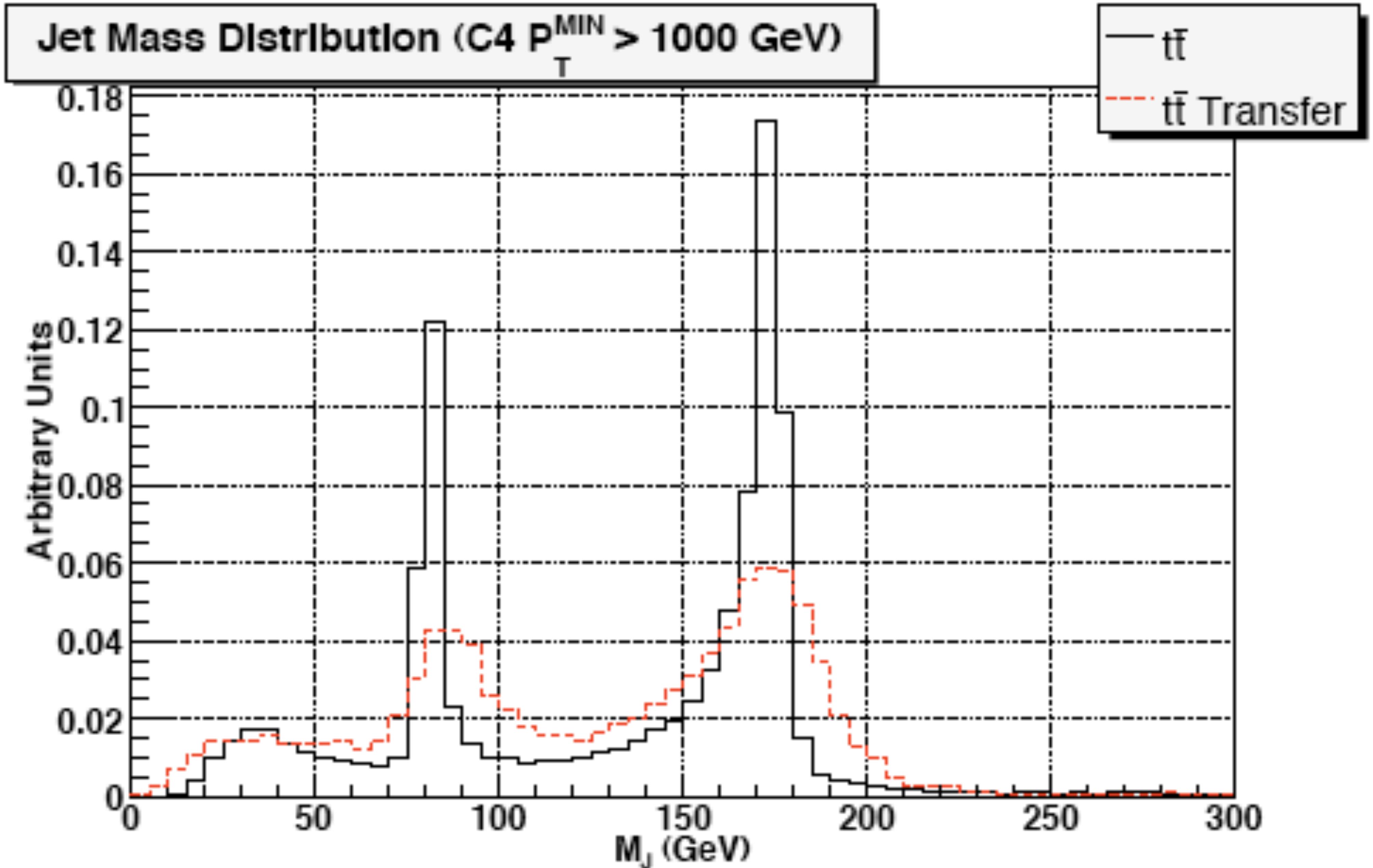
Pure kinematical
bW(qq) dist'
in/out cone
much longer

Cone top-jet mass distribution

(Fleming, Hoang, Jain, Mantry, Scimemi, Stewart) Almeida, SJL, Perez, Sterman, Sung, & Virzi, to appear.

Sherpa => Full Simulation
(CKKW)

Preliminary (Transfer function "Full Simulation")



QCD cone jet mass distribution

Boosted QCD Jet via factorization:

$$\frac{d\sigma^{Q(G)}_{theory}}{dm_J} = \int_{p_T{}^{min}}^{\infty} dp_T \, \frac{d\sigma\left(p_T\right)}{dp_T} \, J^{Q(G)}\left(m, p_T, R\right)$$

Full expression:

$$\frac{d\sigma_{H_A H_B \to J_1 J_2}}{dm^2_{J_1} dm^2_{J_2} d\eta} = \sum_{abcd} \int dx_a \, dx_b \, \phi_a(x_a, p_T) \, \phi_b(x_b, p_T) \frac{d\hat{\sigma}_{ab \to cd}}{dp_T d\eta} \left(x_a, x_b, \eta, p_T\right)$$
$$S\left(m^2_{J_1}, m^2_{J_2}, \eta, p_T, R^2\right) \; J_1^{(c)}\left(m^2_{J_1}, \eta, p_T, R^2\right) J_2^{(d)}\left(m^2_{J_2}, \eta, p_T, R^2\right)$$

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For large jet mass & small R,
no big logs =>
J^i can be calculated via
perturbative QCD!

Full expression:

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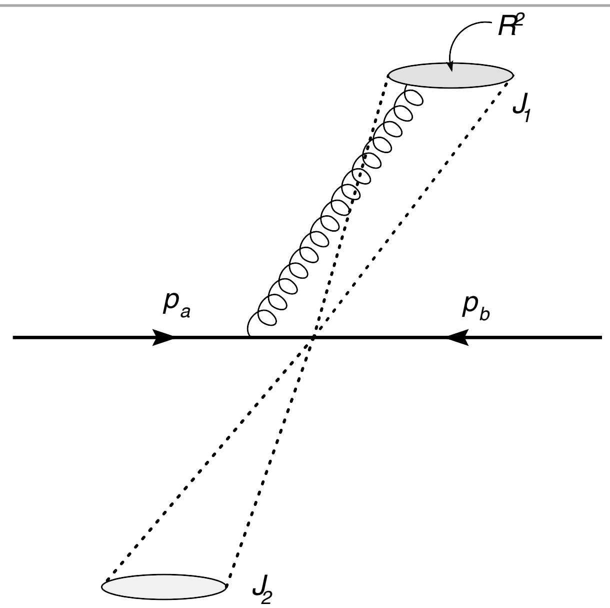
QCD Jet mass distribution, Q+G

Main idea: calculating mass due to two-body QCD bremsstrahlung:



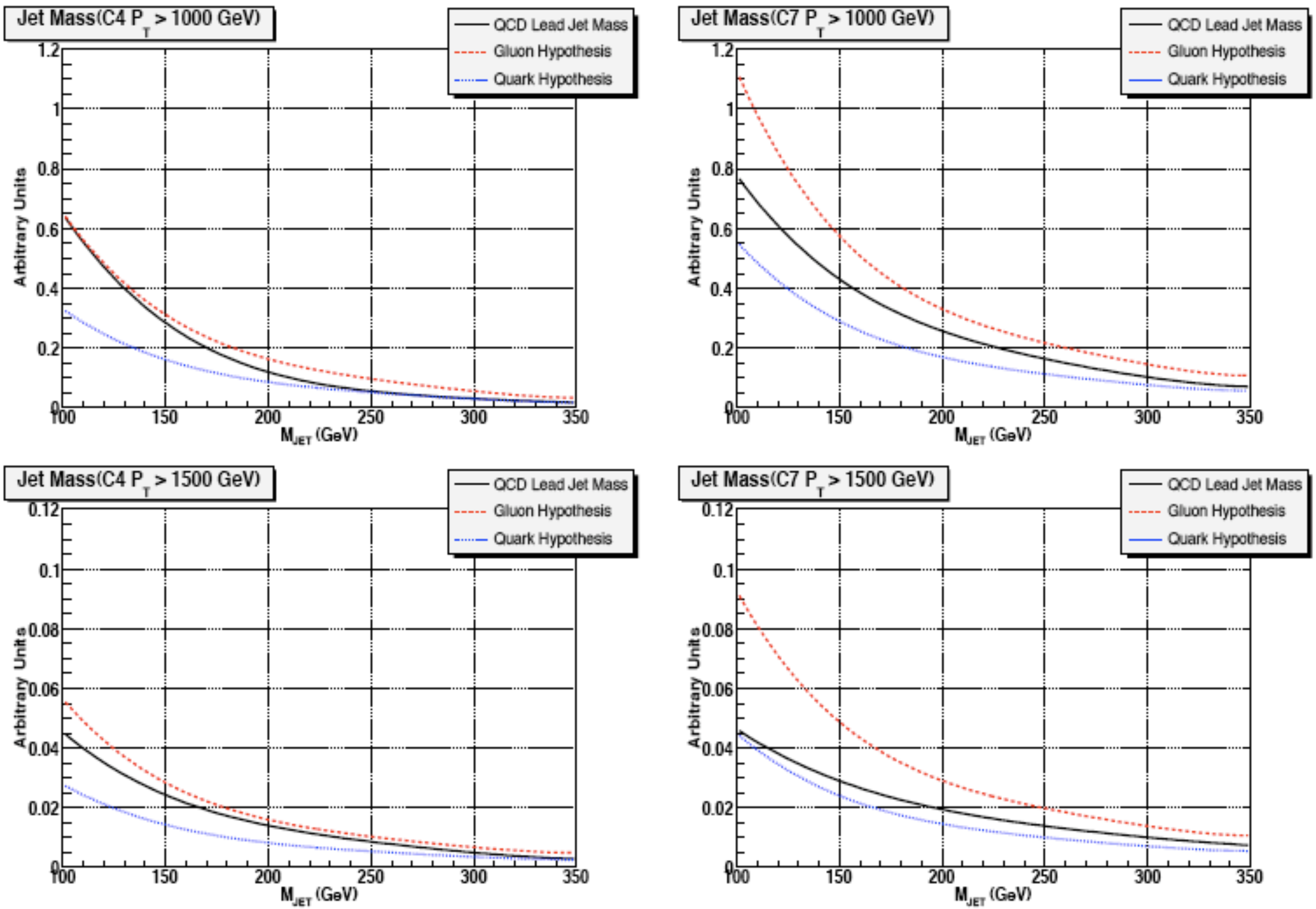
$$J^Q(m_J, p_T, R) = \frac{C_F}{\pi\, m_J\, p_T}\int_{k_{min}}^{p_T/2} dk\, \alpha_S(k)\Big(\frac{2k^2}{(p_T-k)^2} + \frac{2k^2 - p_T\, k + 2p_T^2}{k(p_T-k)} + \frac{m^2(2k^3 - p_T k^2 - 6p_T^2 k + 2p_T^3)}{4p_T^2\, k^2(p_T-k)}\Big),$$

$$J^G(m_J, p_T, R) = \frac{C_A}{\pi\, m_J\, p_T^2}\int_{k_{min}}^{p_T/2} dk\, \alpha_S(k)\frac{1}{8k^2(k-p_T)^2}\Big(24k^5 - 56k^4 p_T + 2m_J^2 p_T^3 - 8k^2 p_T(m_J^2 + 5p_T^2) + 8k^3(m_J^2 + 9p_T^2) + k(-5m_J^2 p_T^2 + 16p_T^4)\Big),$$

where $C_F = \frac{4}{3}$, $C_A = 3$ and $k_{min} = \frac{m^2/(2p_T)}{1-\sqrt{1-m^2/p_T^2}\,\cos R}$.

Jet mass distribution theory vs. MC

Sherpa, jet function convolved



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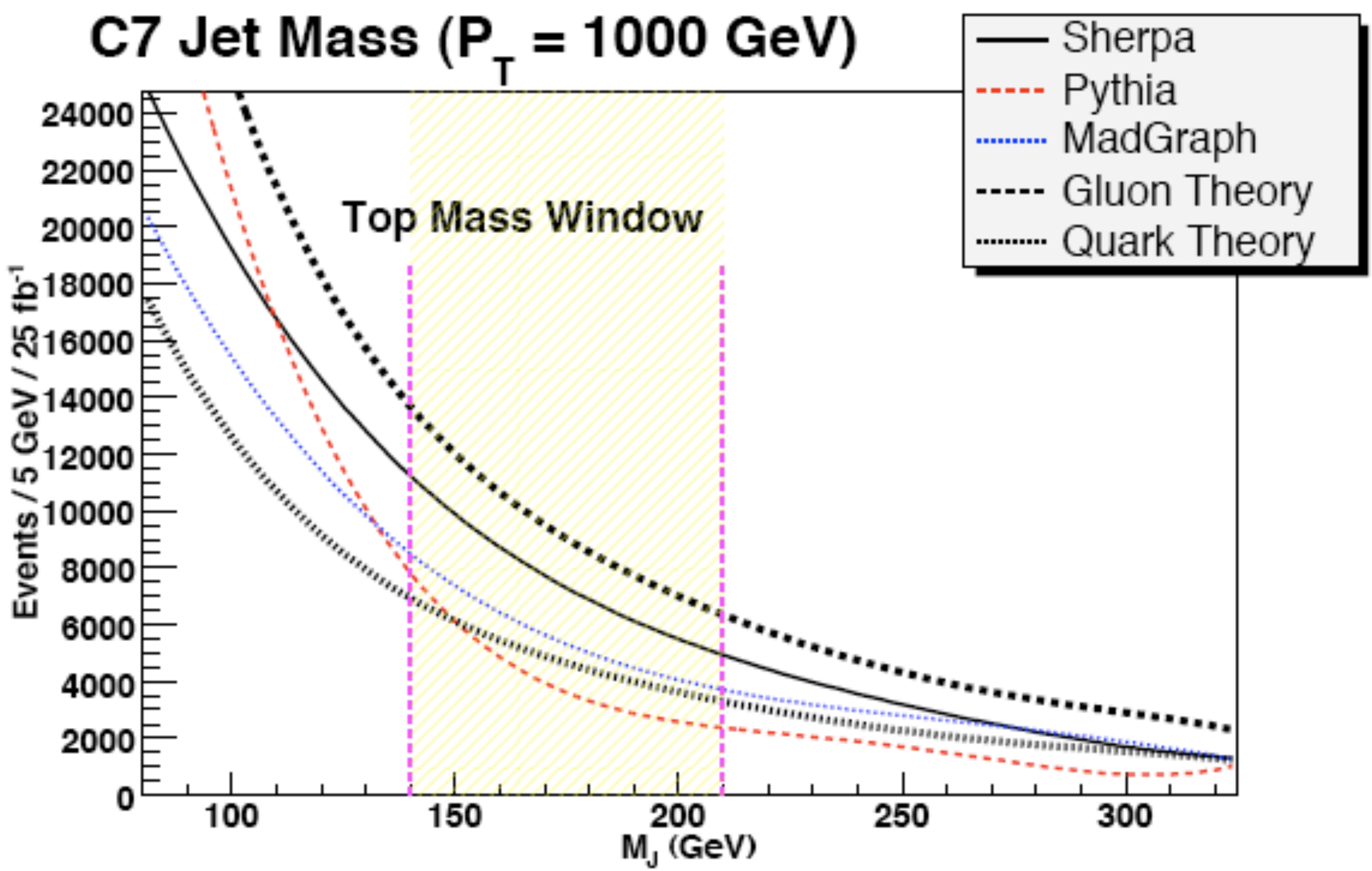
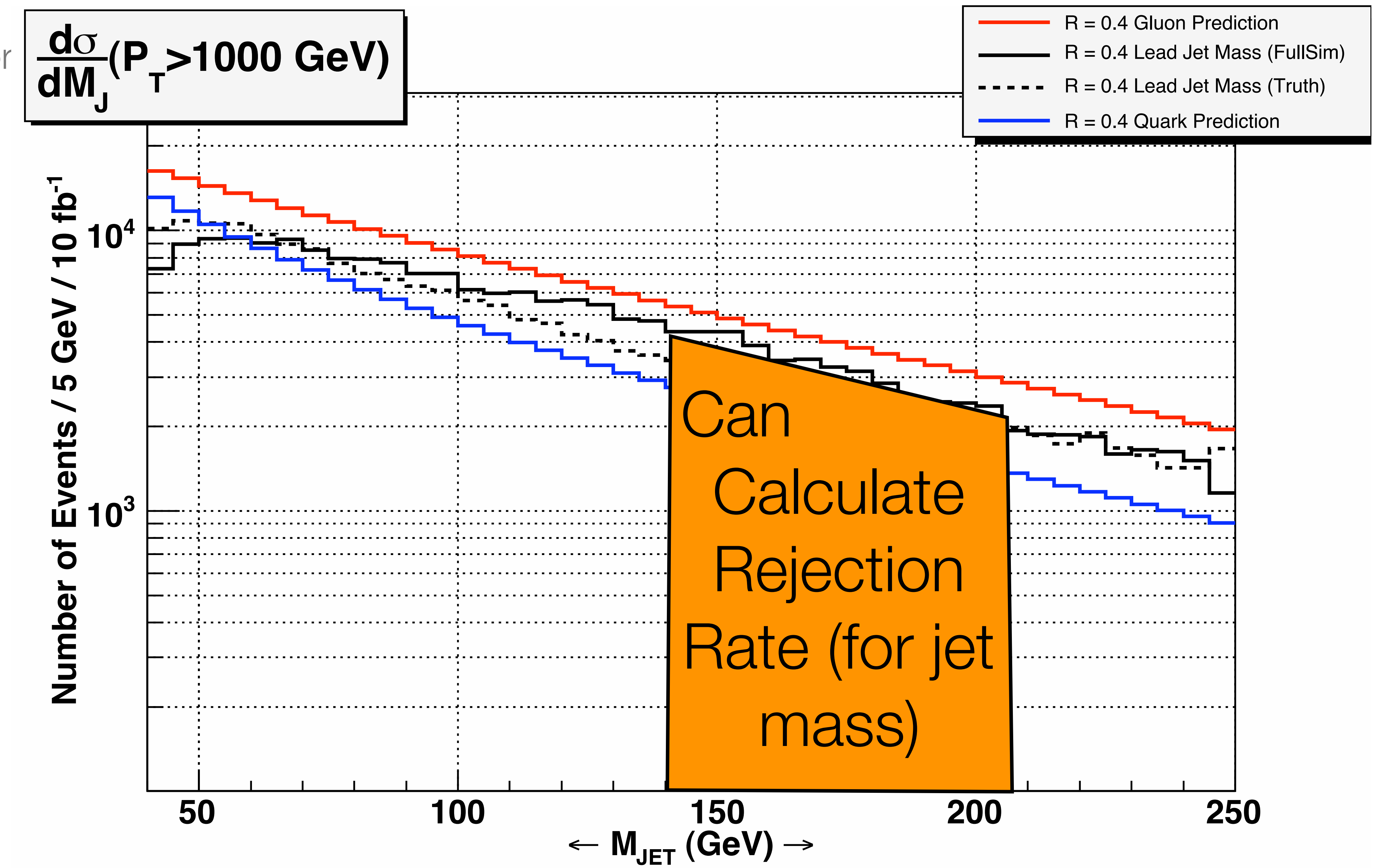


QCD jet mass dist' under control!

Almeida, SJL, Perez, Sterman, Sung, & Virzi, to appear.

Sherpa (CKKW)
With Full Detector
Simulation



QCD jet mass dist' under control!

✦Rejection Ratio: (#of events for m_t-Δ < m_J < m_t+Δ) / (total # of events)

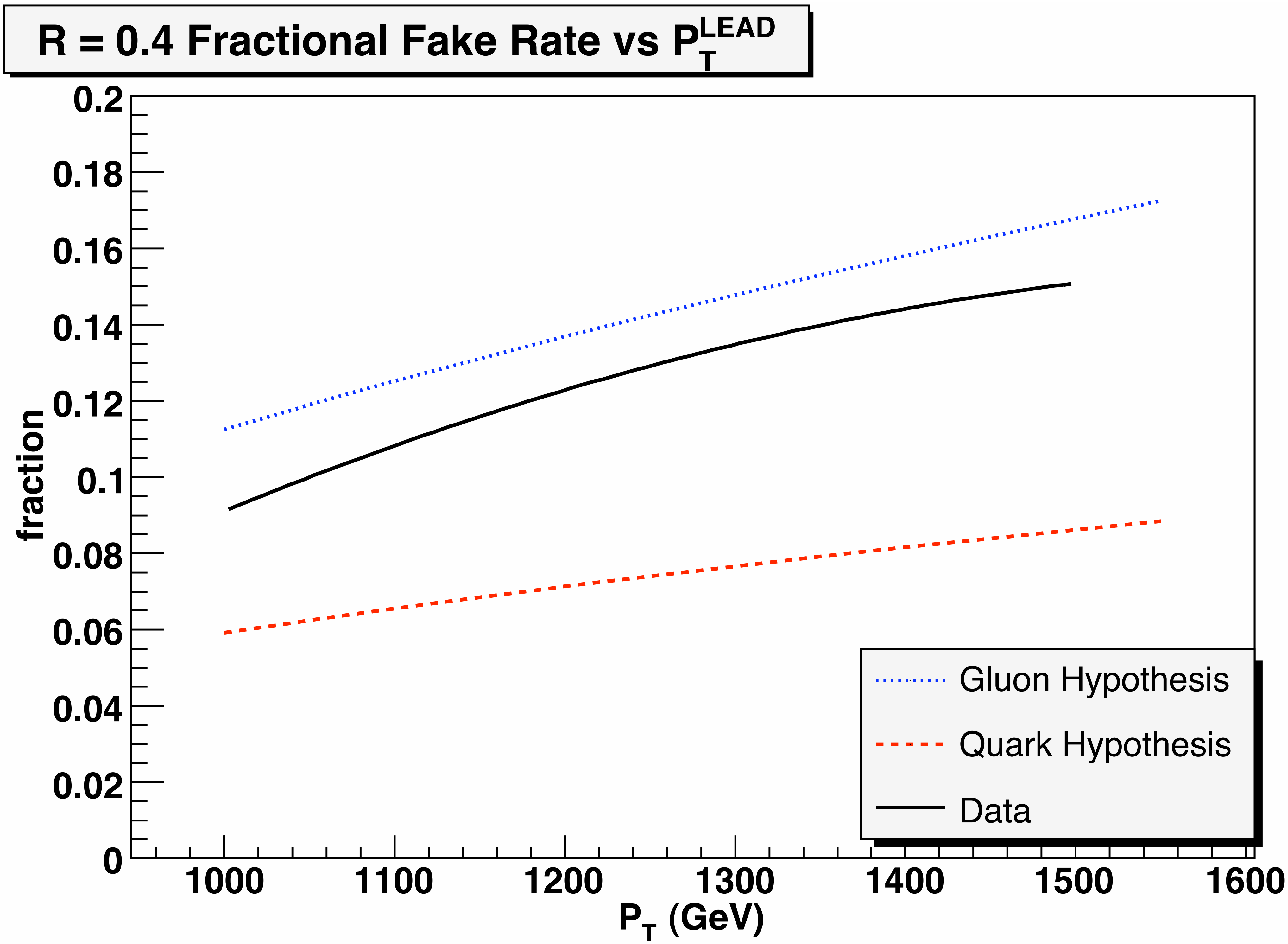
- Can use our jet function to calculate it:

$$\boxed{\int_{140\ GeV}^{210\ GeV} dm_J\, J^Q(m_J, p_T, R) \leq \text{ fake rate } \leq \int_{140\ GeV}^{210\ GeV} dm_J\, J^G(m_J, p_T, R)}$$

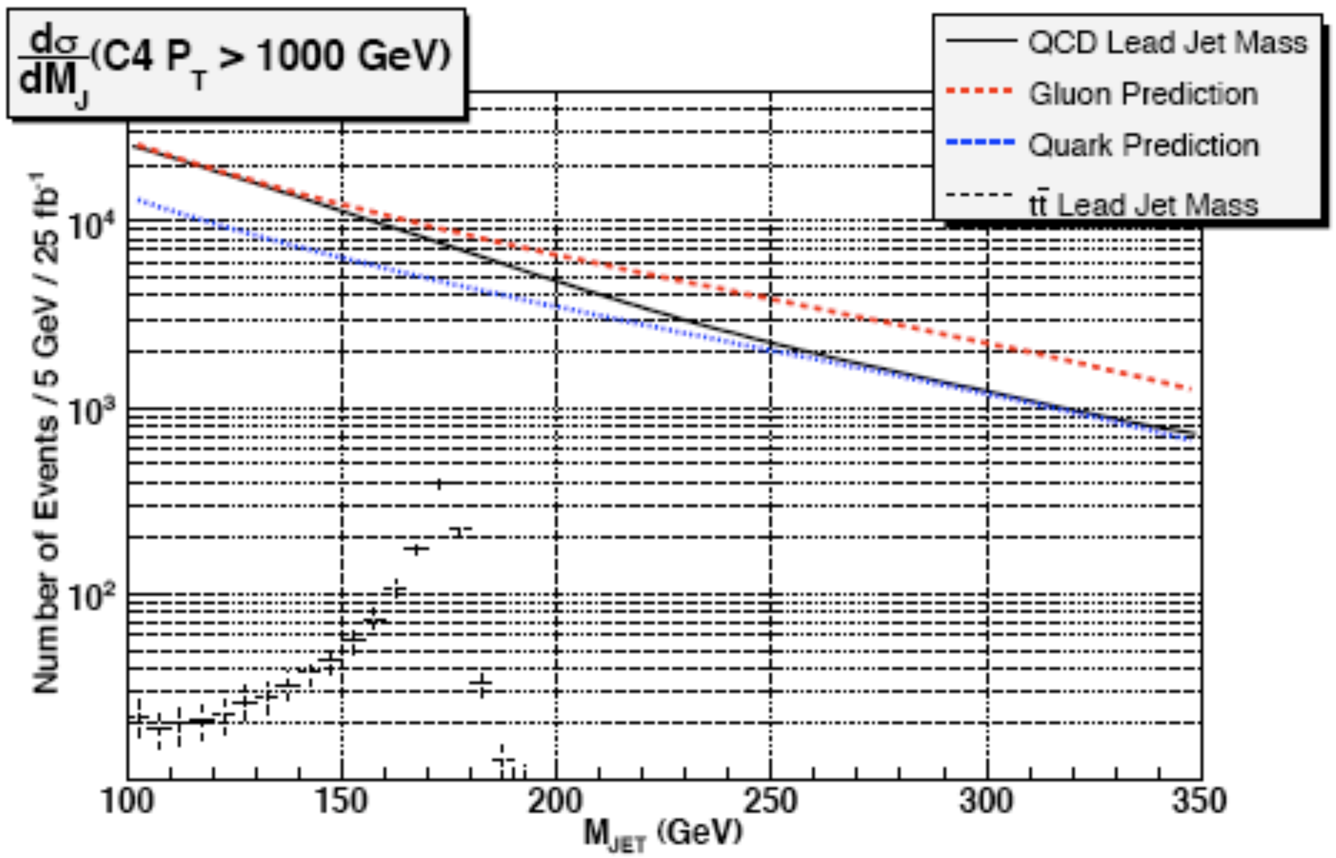
- Matches well with MC simulation (within 10%)

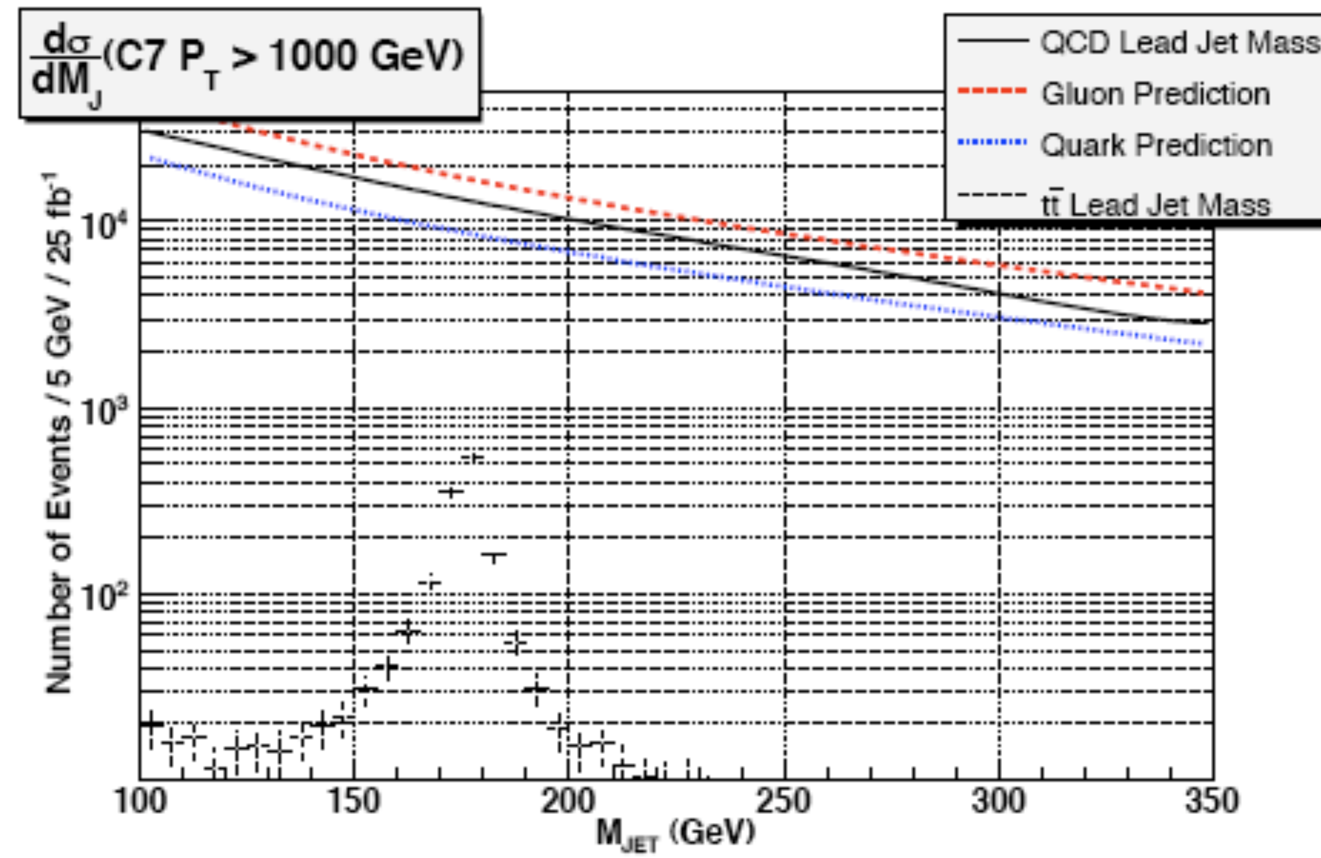
- For QCD dijet background, double mass tagging will reduce the background (typically, $\epsilon_r \sim 15\%$)

QCD jet mass dist' under control!



Ex. SM ttbar vs. di-jet background!





With trasf … lation”)

- b-tagging efficiency for highly boosted tops is wired (small ~20%)

Ex. SM ttbar vs. di-jet background!

Jet Energy Scale	Cone Size	${p_T}^{1,2}$ cut	Signal	Background	$\frac{S}{B}$	$\frac{S}{\sqrt{S+B}}$
0.0	C4	1000 GeV	293	9397	0.031	3.0
0.0	C7	1000 GeV	478	24331	0.020	3.0
5%	C4	1000 GeV	358	11392	0.031	3.3
5%	C7	1000 GeV	616	31306	0.020	3.4
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significance for d ... g 25 fb^{-1}

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look hopeless ... n b-taggs!

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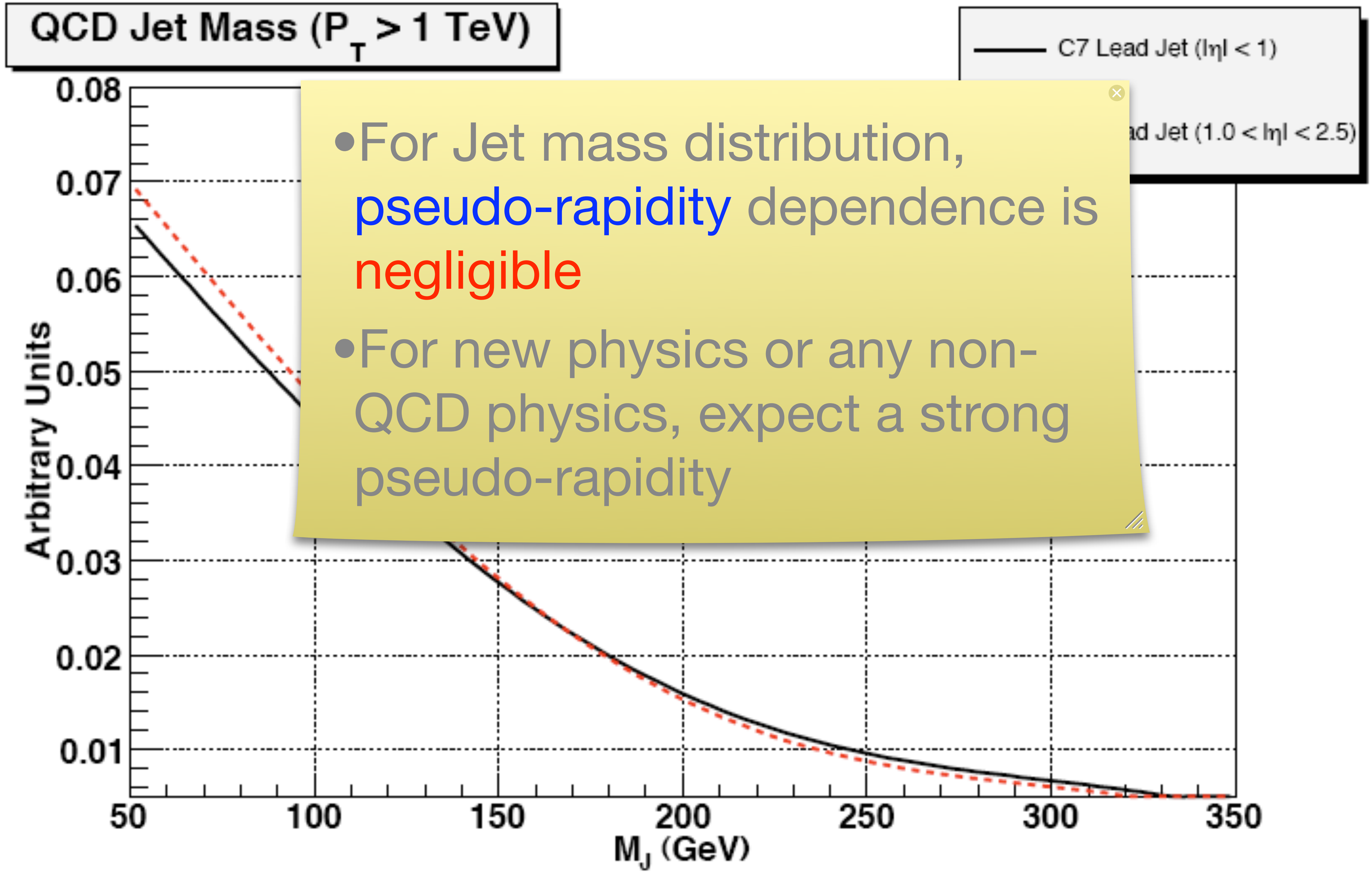
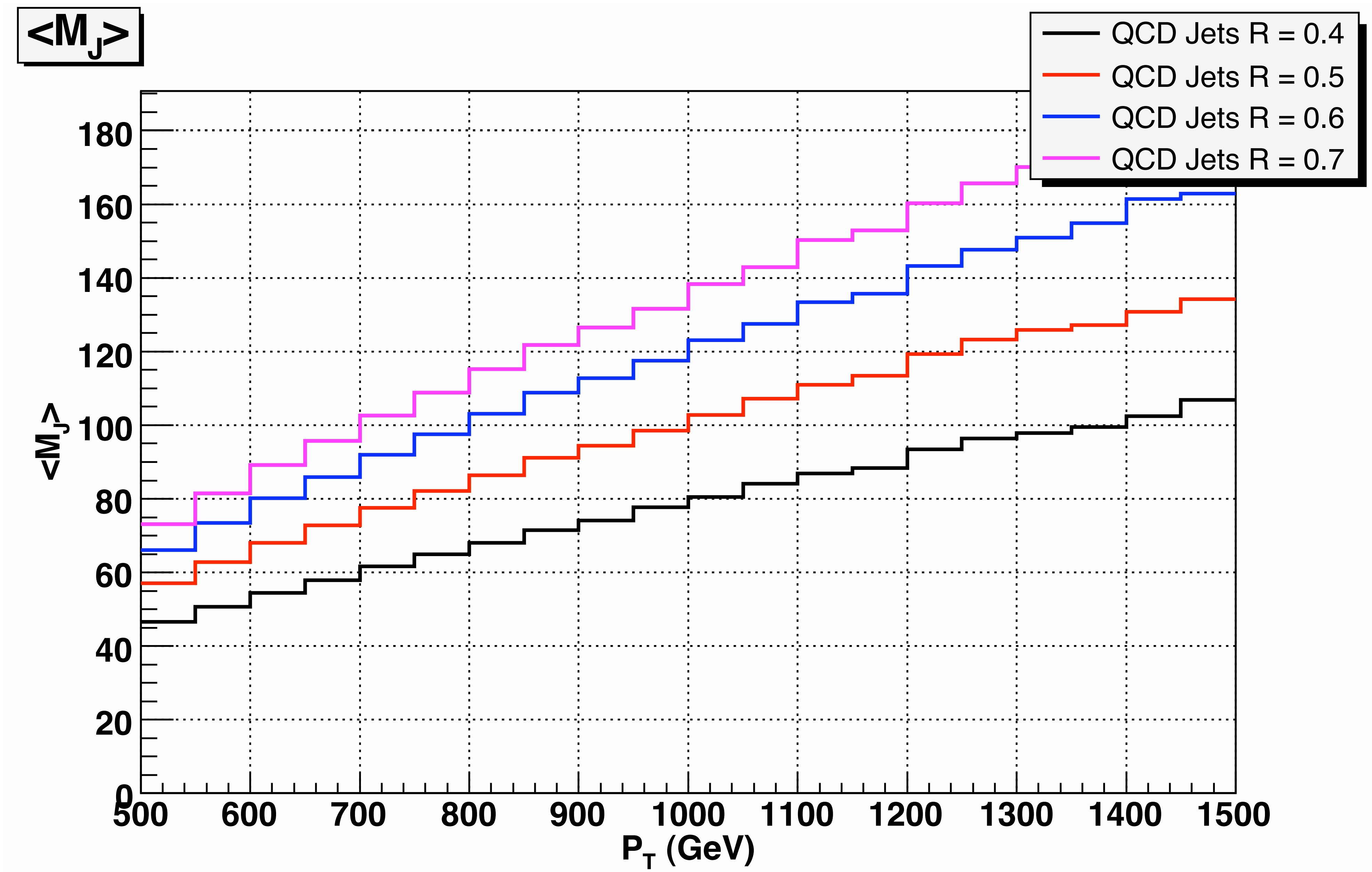
Pseudo-rapidity independence



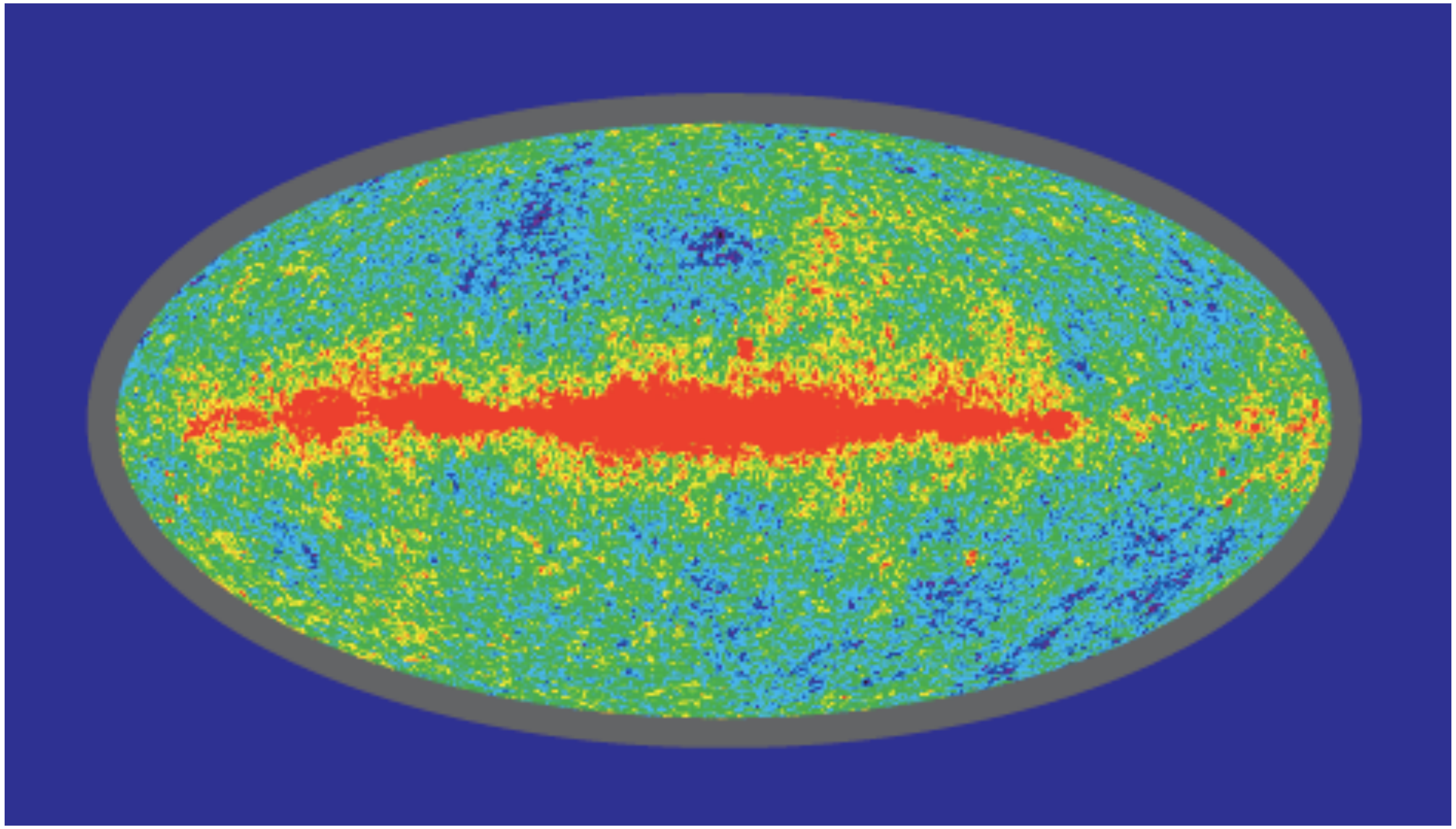
- For Jet mass distribution, pseudo-rapidity dependence is negligible
- For new physics or any non-QCD physics, expect a strong pseudo-rapidity

Average Jet Mass (IR Mass cut needed)

$$\langle M_J \rangle \propto P_T \,,\ R$$



Jet sub-structure



Why jets? What else?

- QCD amplitudes have soft-collinear singularity

- Observable: IR safe, smooth function of E flow

Sterman & Weinberg, PRL (77)

- Jet is a very inclusive object, defined via direction + p_T (+ mass)

- Even R=0.4 contains O(100) had-cells => huge amount of info' is lost

Jet-shapes

- “Jet-shapes” = inclusive observables dependent on energy flow within individual jets
- Once jet mass is fixed at a high scale
  - ➡ Large class of jet-shapes become perturbatively calculable
  - ➡ IR safe jet-shapes combined with IR safe jet algorithm provide a bridge between

  Direct theory prediction $\longleftrightarrow$ Data/MC output

Jet-shapes

- “Jet-sh… bles
  dep… ual jets

je… e

Direct the… ata/MC co… t

Can analyze a single event by a
variety of jet shapes
=> the resolution associated with
each one need not be dramatic!

IR-safe jet-shapes which know top from QCD jets?

- Successes in high jet mass => jet function is well described by single gluon radiation

- QCD, top: linear, planar E-deposition in the cone

Almeida, SJL, Perez, Sterman, Sung, & Virzi, arXiv:0807.0234

c.f. Wang, Thale: similar event shape, "sphericity tensor" arXiv:0806.0023

- IR-safe E-flow tensor: $I_w^{kl} = \frac{1}{m_J} \sum_i w_i \frac{p_{i,k}}{w_i} \frac{p_{i,l}}{w_i}$

- Planar flow: $Pf = \frac{4\det(I_w)}{\mathrm{tr}(I_w)^2} = \frac{4\lambda_1\lambda_2}{(\lambda_1+\lambda_2)^2}$

Planar flow (Pf), QCD vs top jets

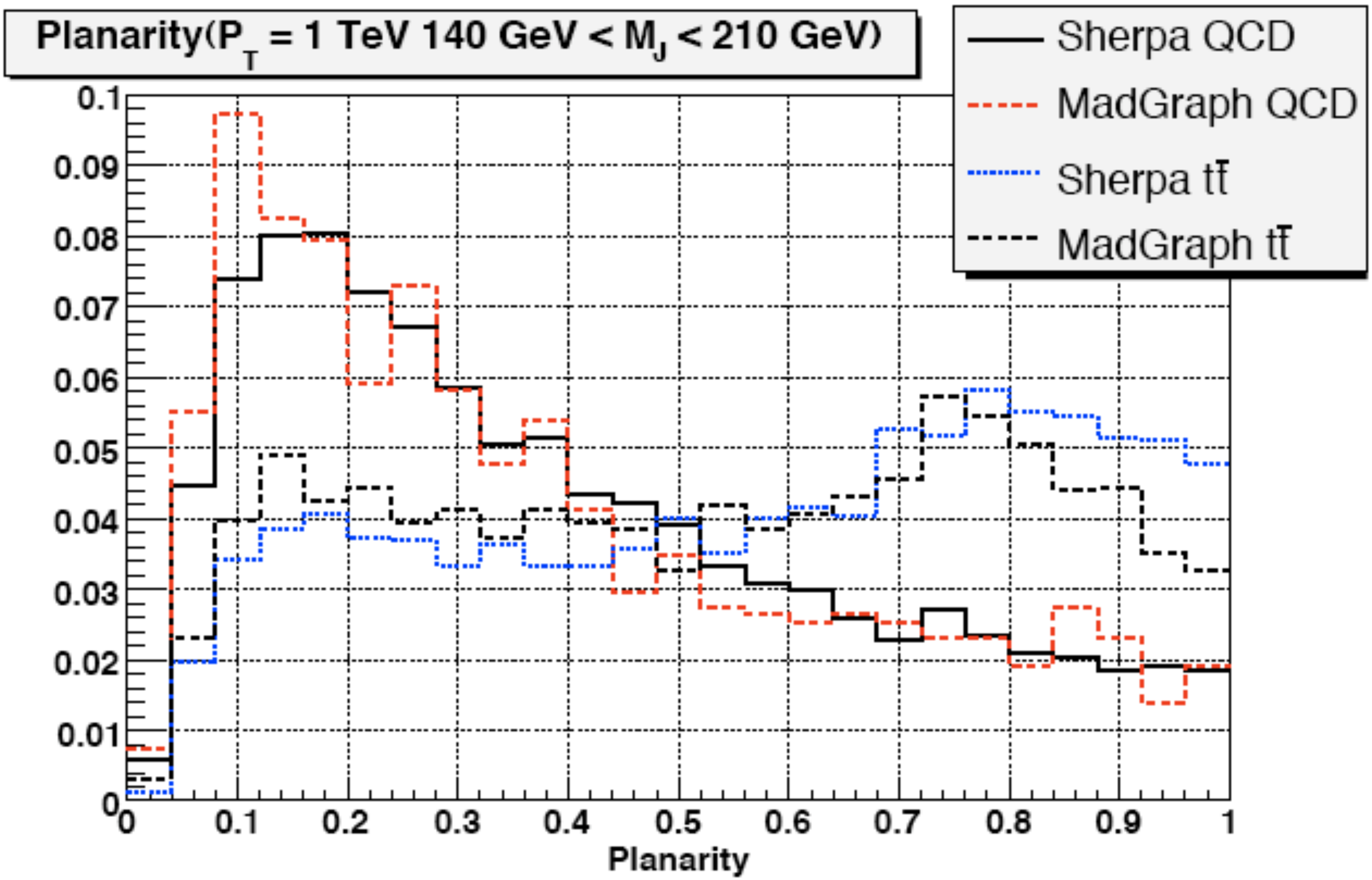
- LO: Pf ~ 0 for QCD (2-body decay)

$$\frac{1}{J}\left(\frac{dJ}{dPf}\right)_{\rm 2body} = \delta(Pf)$$

O(1) for top: smooth
(for istropic ≥ 3-body decay, Pf~1)

- NLO (due to large m): O(α_s) for QCD
nominal for top

Planar flow (Pf), QCD vs top jets



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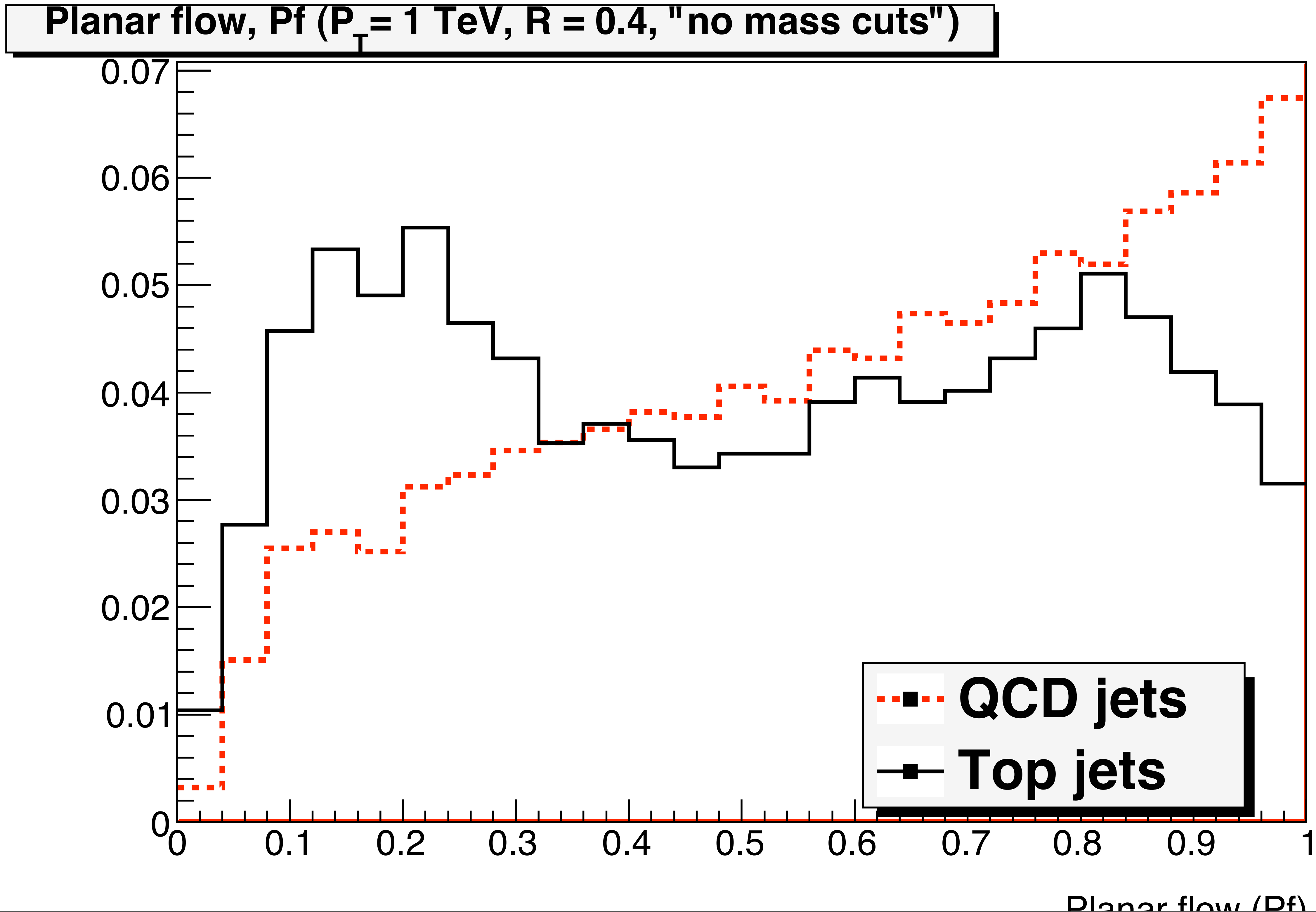


What about 2 body jet, Z/W/h

e.g. see talk by Gopalakrishna (Tue)

Berger, K´ucs and Sterman (03): introduced for e+e- annihilation

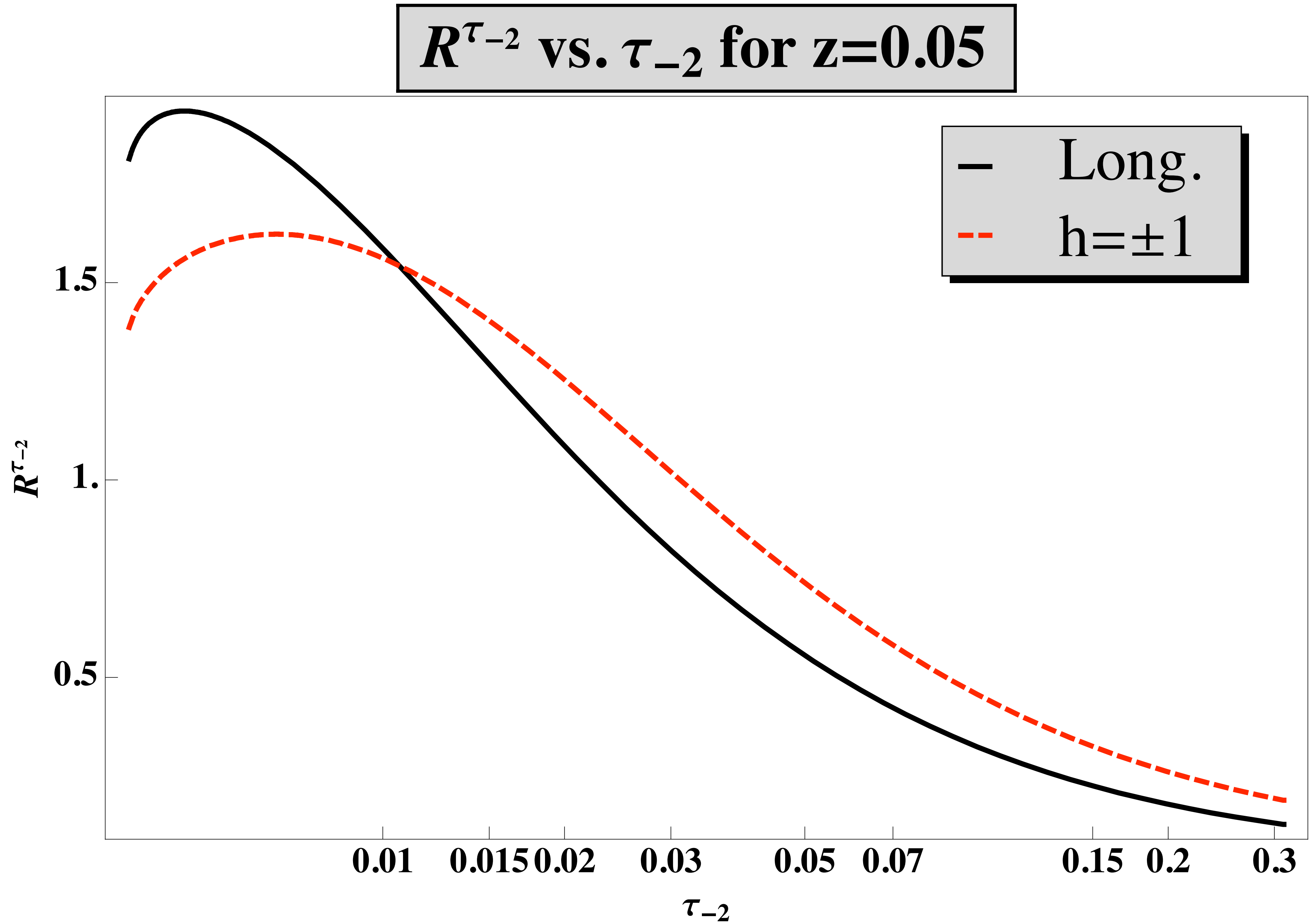
- Angularities on a cone: *Almeida, SJL, Perez, Sterman, Sung, & Virzi,* arXiv:0807.0234

$$\tilde{\tau}_a(R, p_T) = \frac{1}{m_J} \sum_{i \in jet} \omega_i \, \sin^a\left(\frac{\pi\theta_i}{2R}\right) \left[1 - \cos\left(\frac{\pi\theta_i}{2R}\right)\right]^{1-a}$$

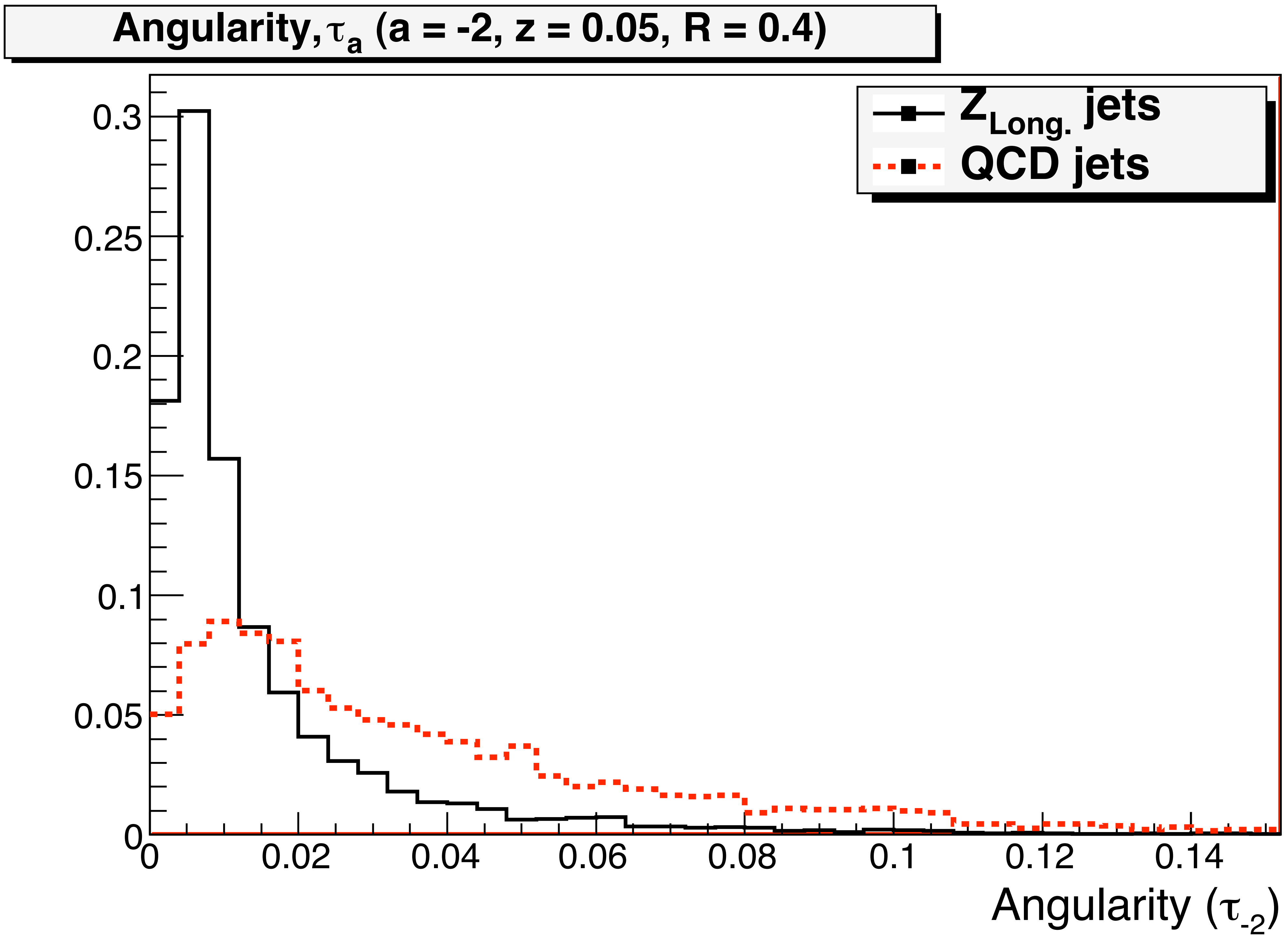
$$P^x(\theta_s) = (dJ^x/d\theta_s)/J^x \Rightarrow P^x(\tilde{\tau}_a)$$

$$R(\tilde{\tau}_a) = \frac{P^{\rm sig}(\tilde{\tau}_a)}{P^{\rm QCD}(\tilde{\tau}_a)}$$

Theory: angularity, QCD vs Z



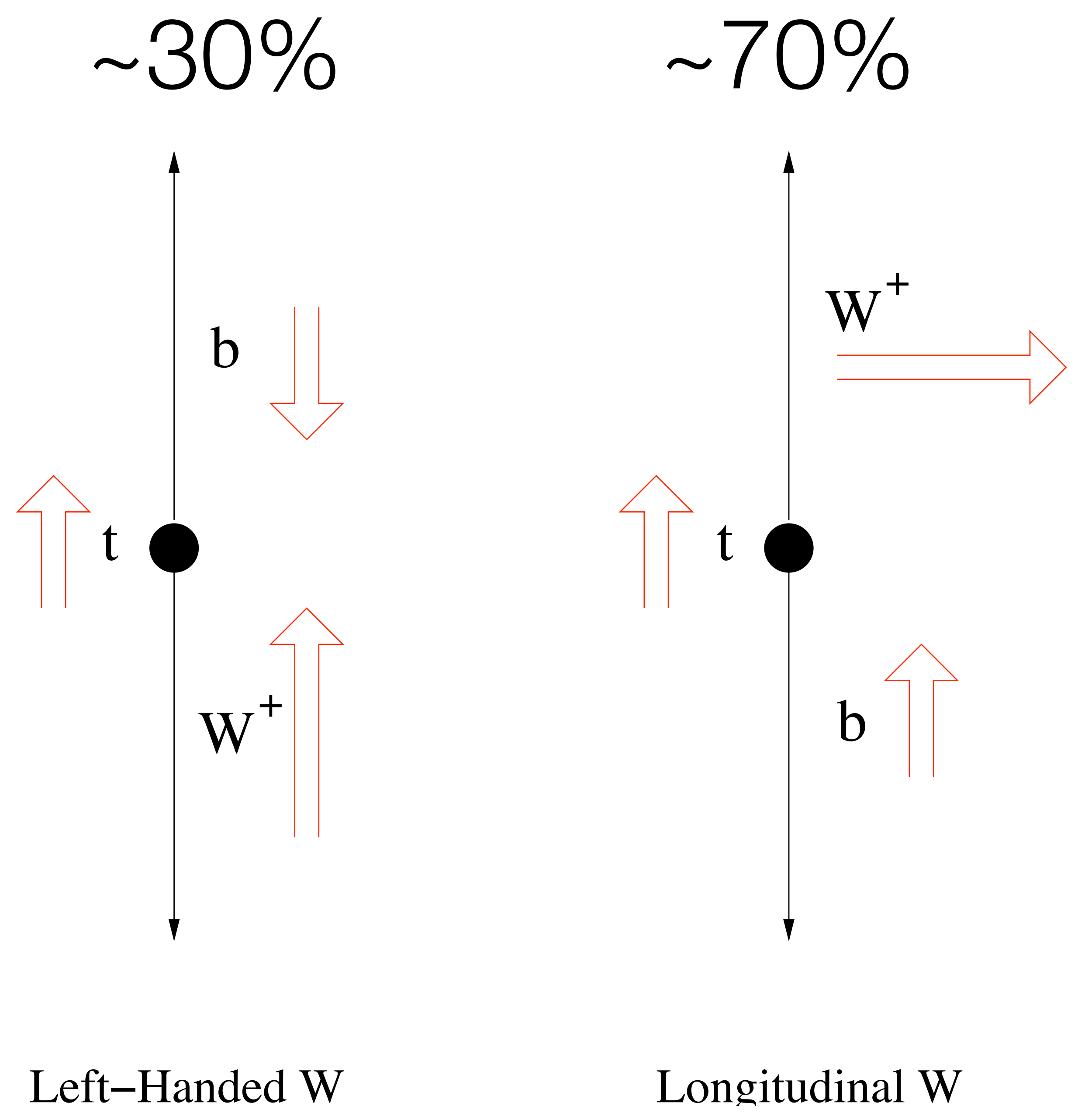
Madgraph: angularity, QCD vs Z



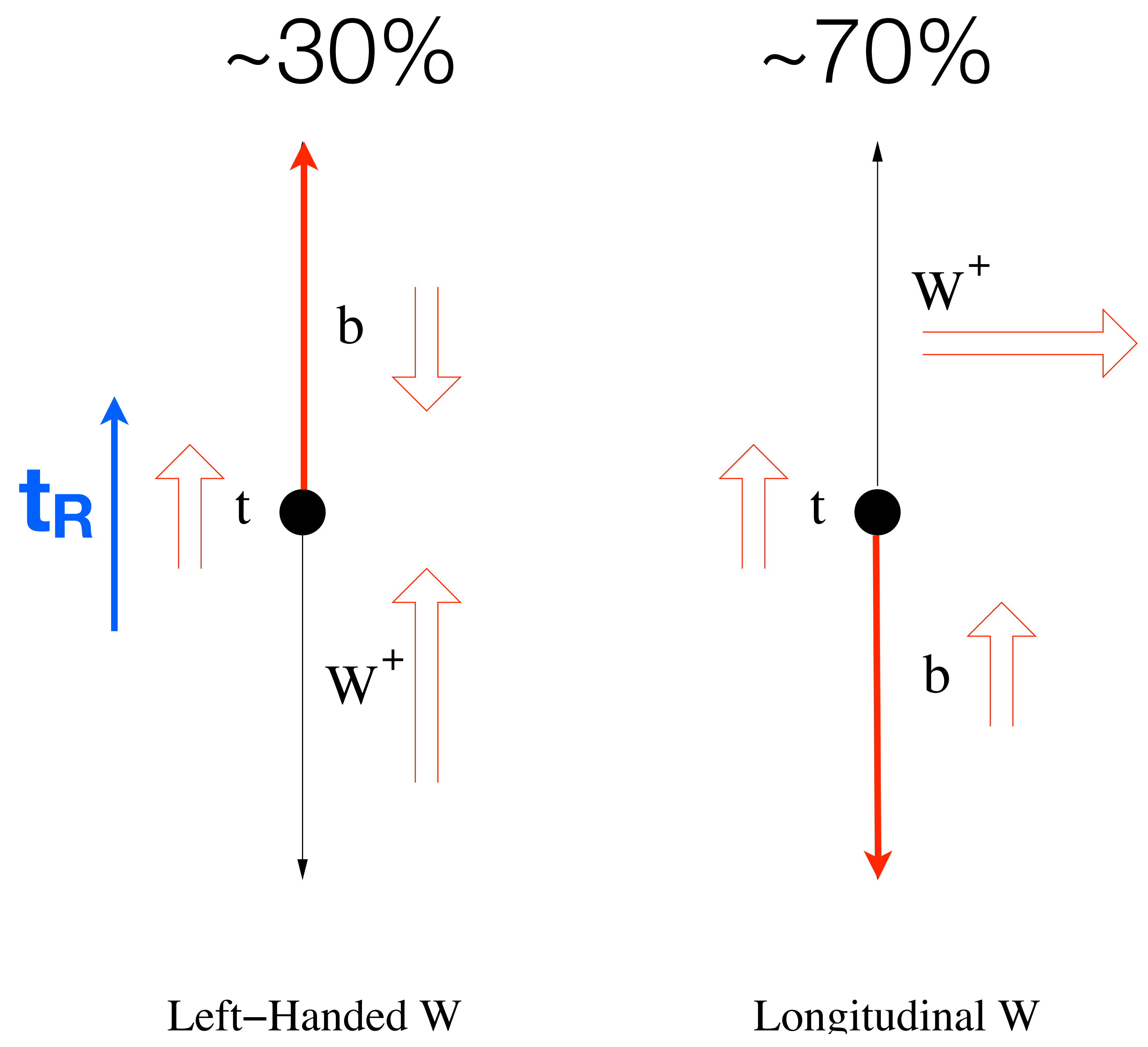
Top Polarization

- Daughter particles remember top polarization
- For Urel' top: helicity=chirality
  - ➡Can do polarization analysis like it was done for the tau
- Want to use P_T to probe top polarization: P_T is a directly measured quantity (c.f. For polarization method, need to use derived quantities with biases, like center of mass boost etc.)
  - Different from spin-spin correlation where you expand in s wave (for non-relativistic top)

Top Polarization

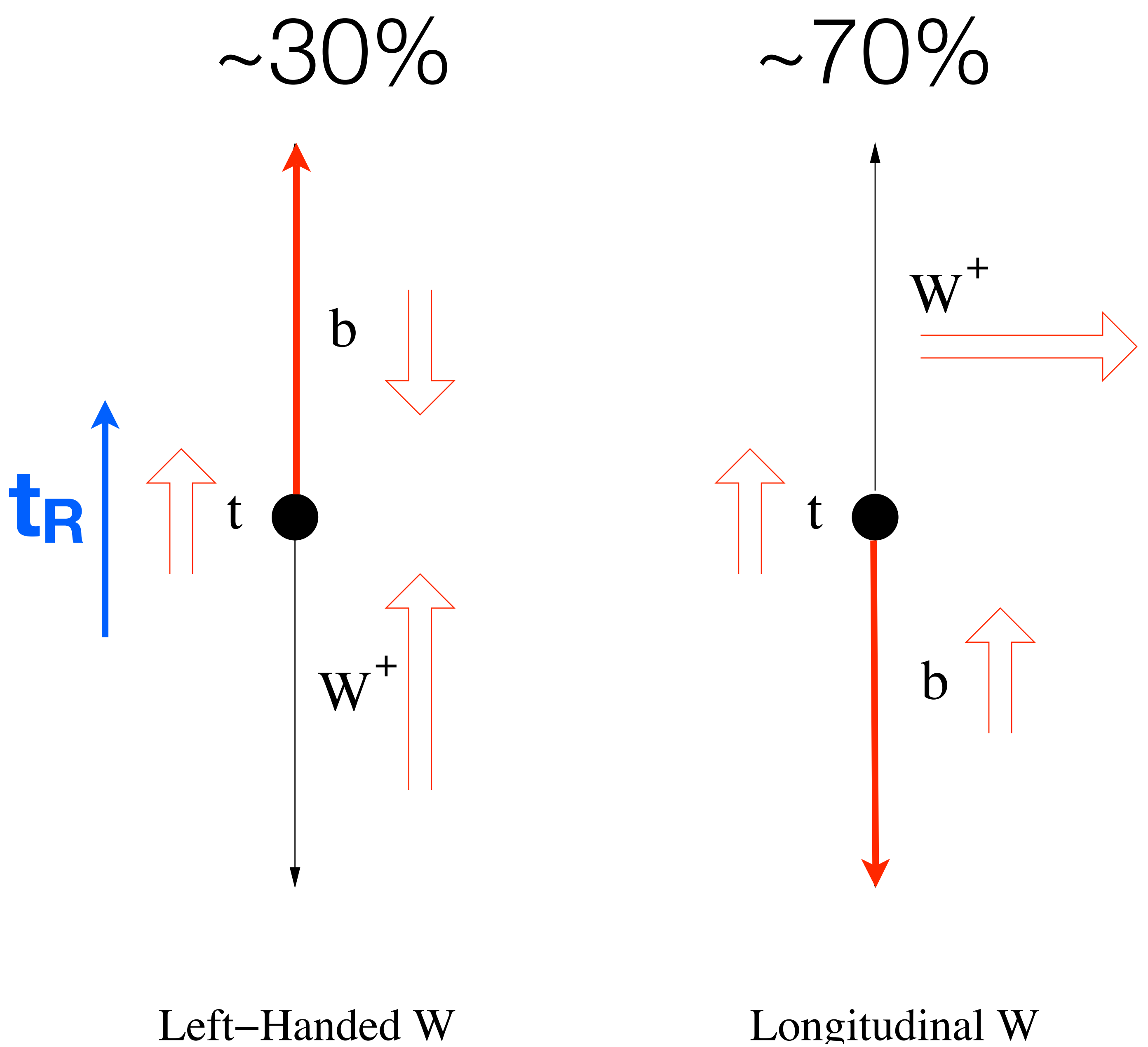


Top Polarization



Top Polarization

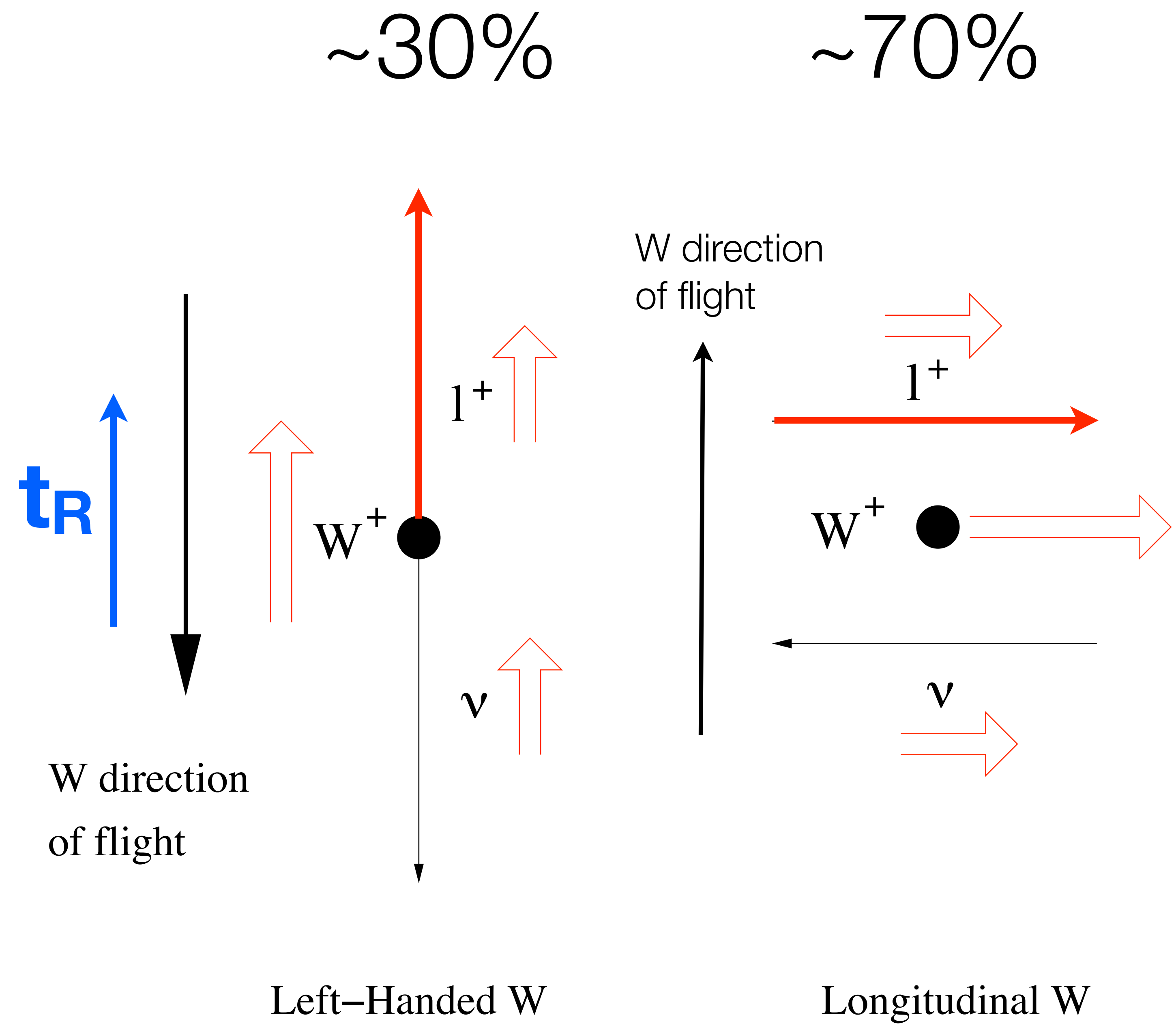
- ✦ b quark:
  - back-warded (soft P_T) for t_R
  - forwarded (hard P_T) for t_L
- ✦ For SM, parity even (PT distribution will be flat) → look for new Physics where parity is violated



Top Polarization

- lepton:forwarded for t_R

  back-warded for t_L



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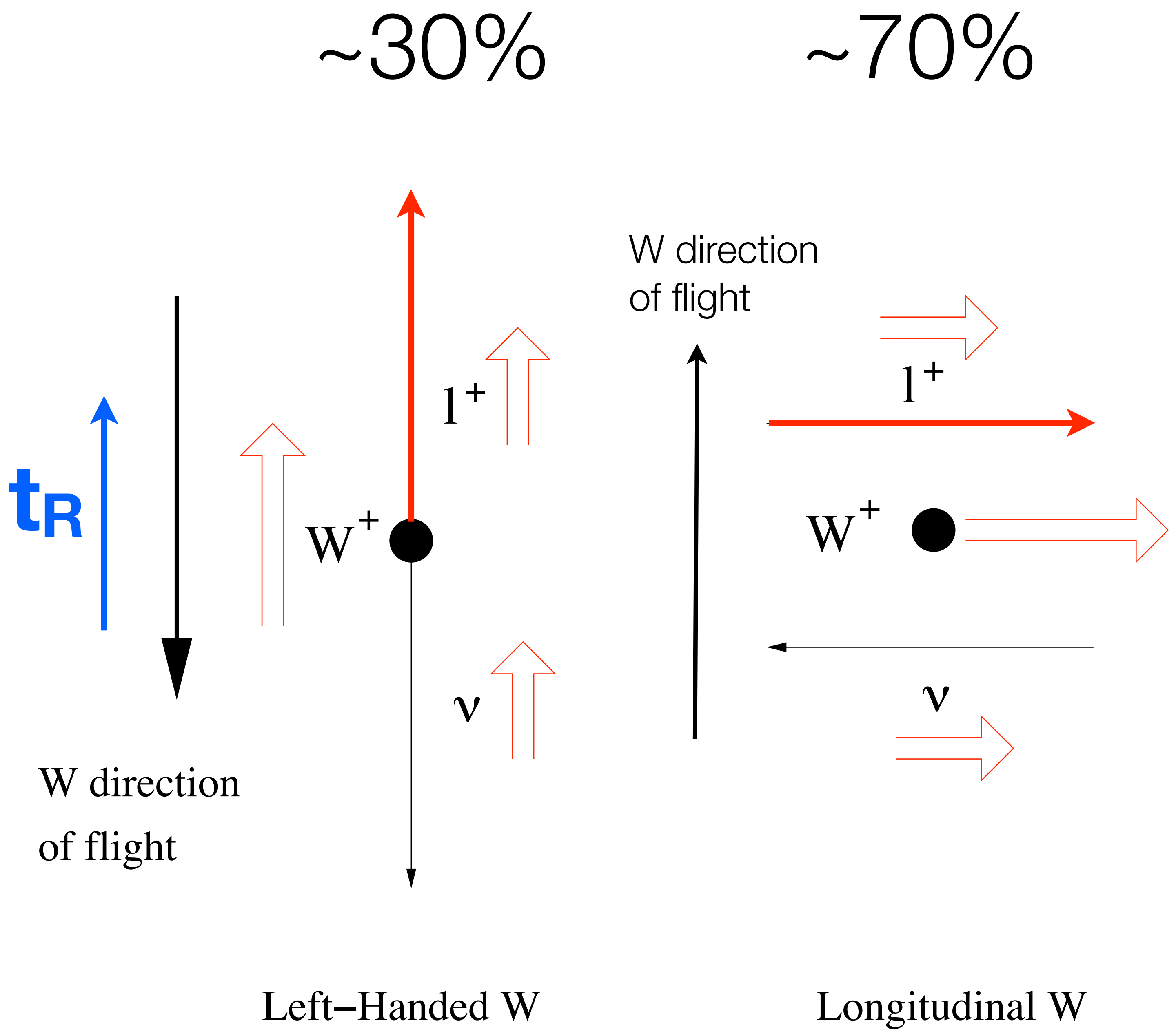
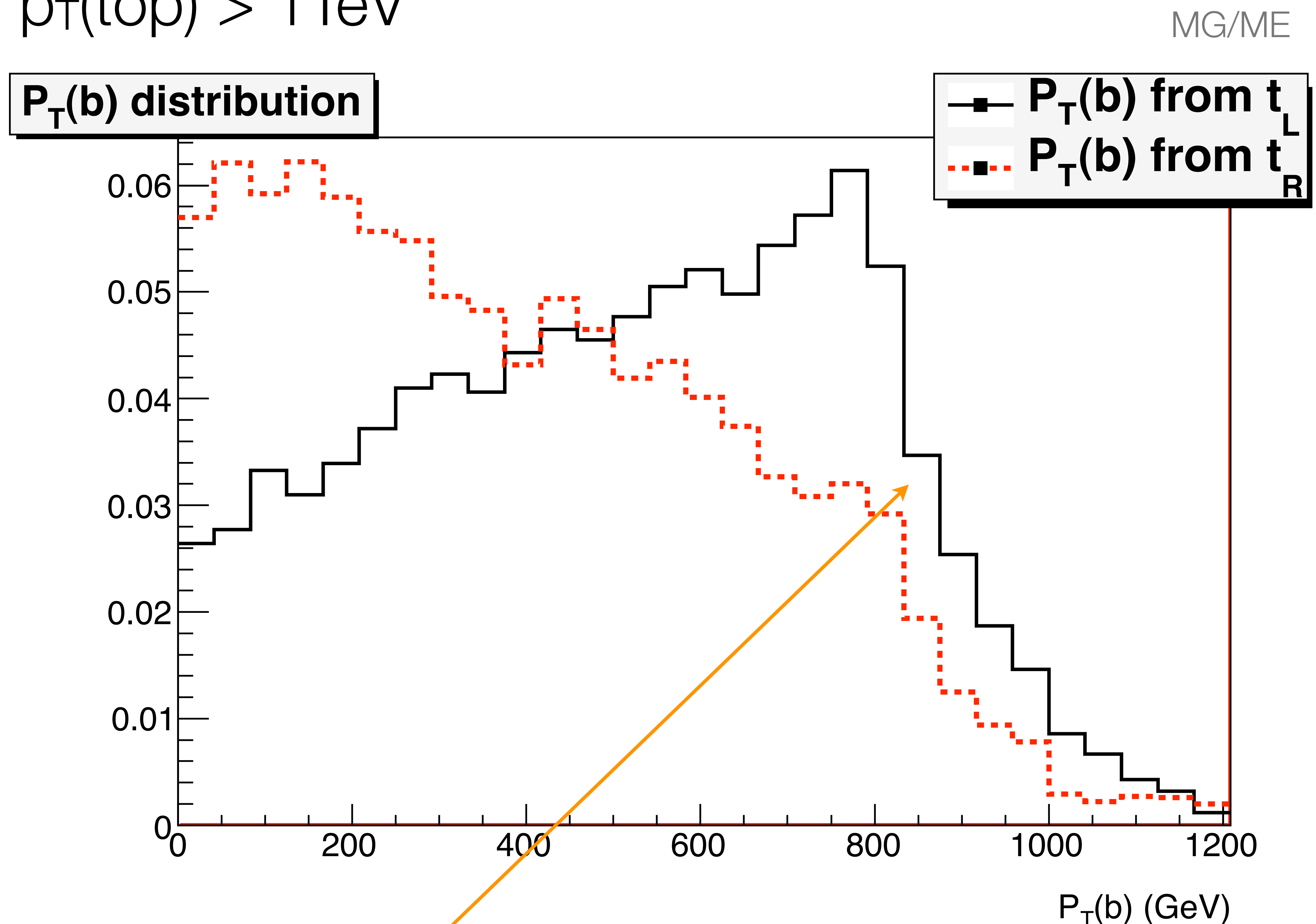
- lepton:forwarded for t_R

  back-warded for t_L



For Boosted Longitudinal W: letpon is forwarded

p_T(top) > 1TeV



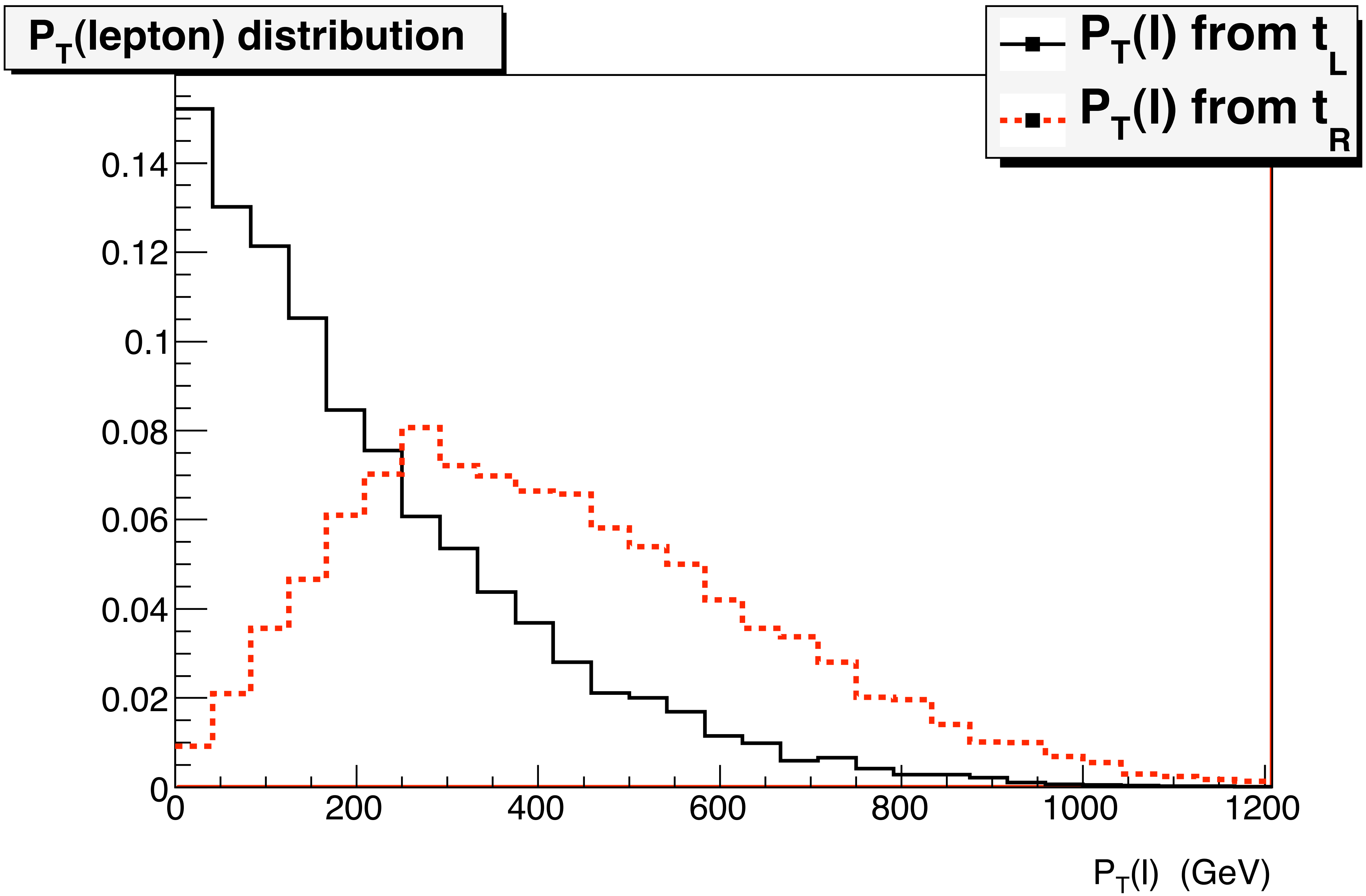
P_T(b) is limited by W boson mass

Hadronic Top

b quark as a spin analyzer

p_T(top) > 1TeV

MG/ME



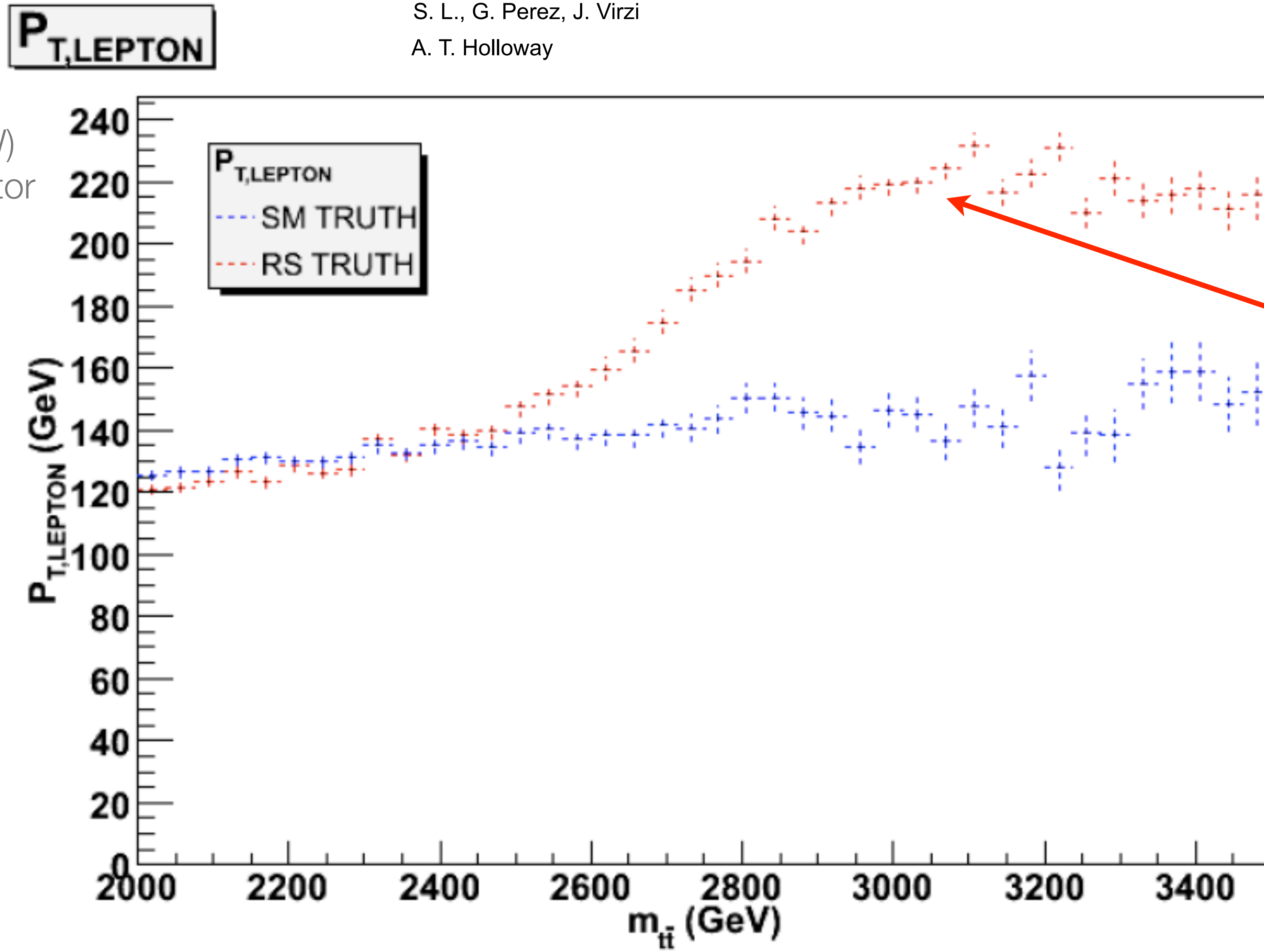
- for example with the KK gluon, you'll see suddenly only leptons/bs that follows the RH curves

Leptonic Top

charged lepton as a spin analyzer

S. L., G. Perez, J. Virzi
A. T. Holloway

Sherpa (CKKW)
Without Detector
Simulation



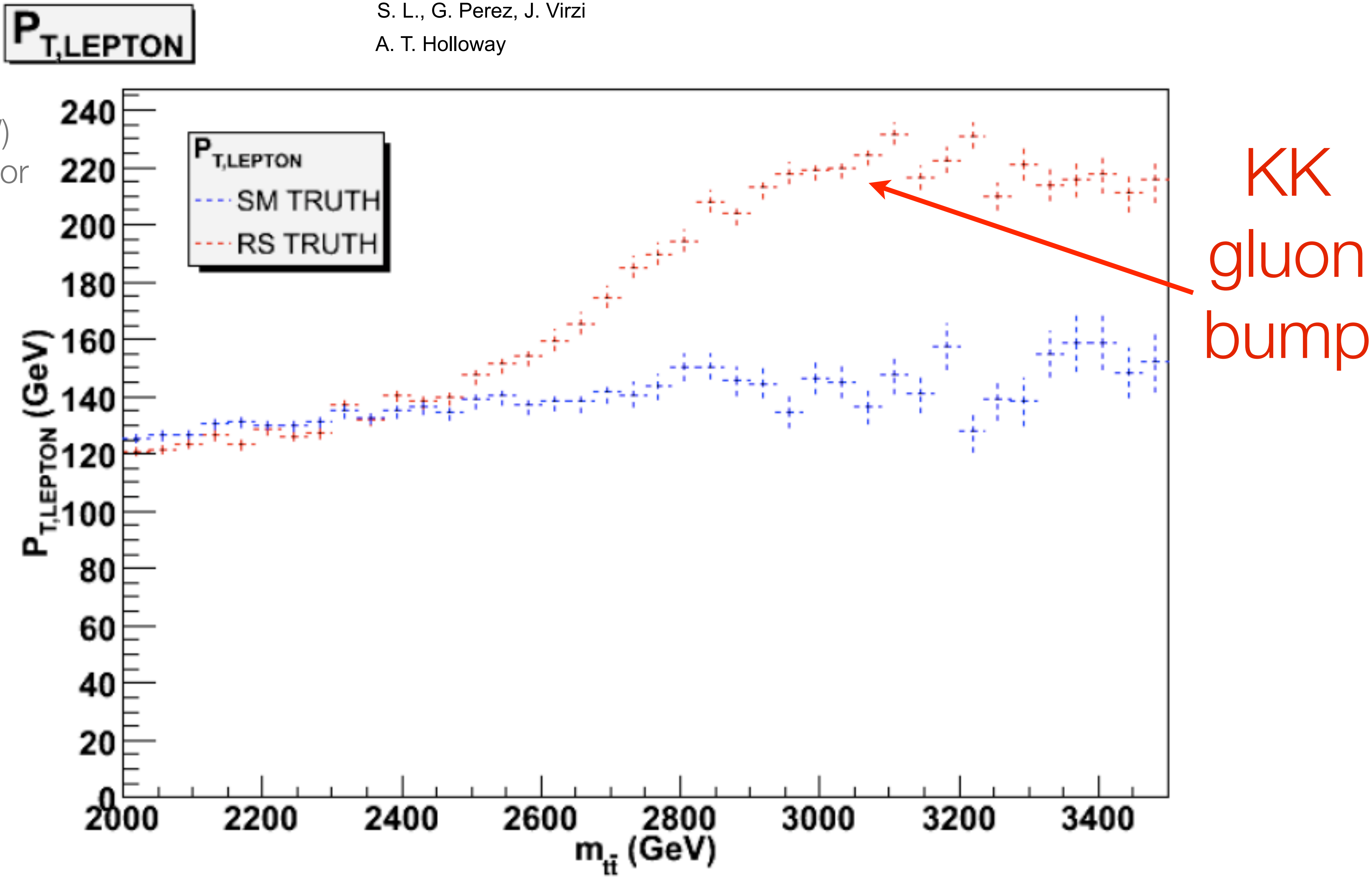
KK
gluon
bump

Example: KK gluon

lepton PT is harder near the KK gluon plateau

S. L., G. Perez, J. Virzi
A. T. Holloway

Sherpa (CKKW)
Without Detector
Simulation

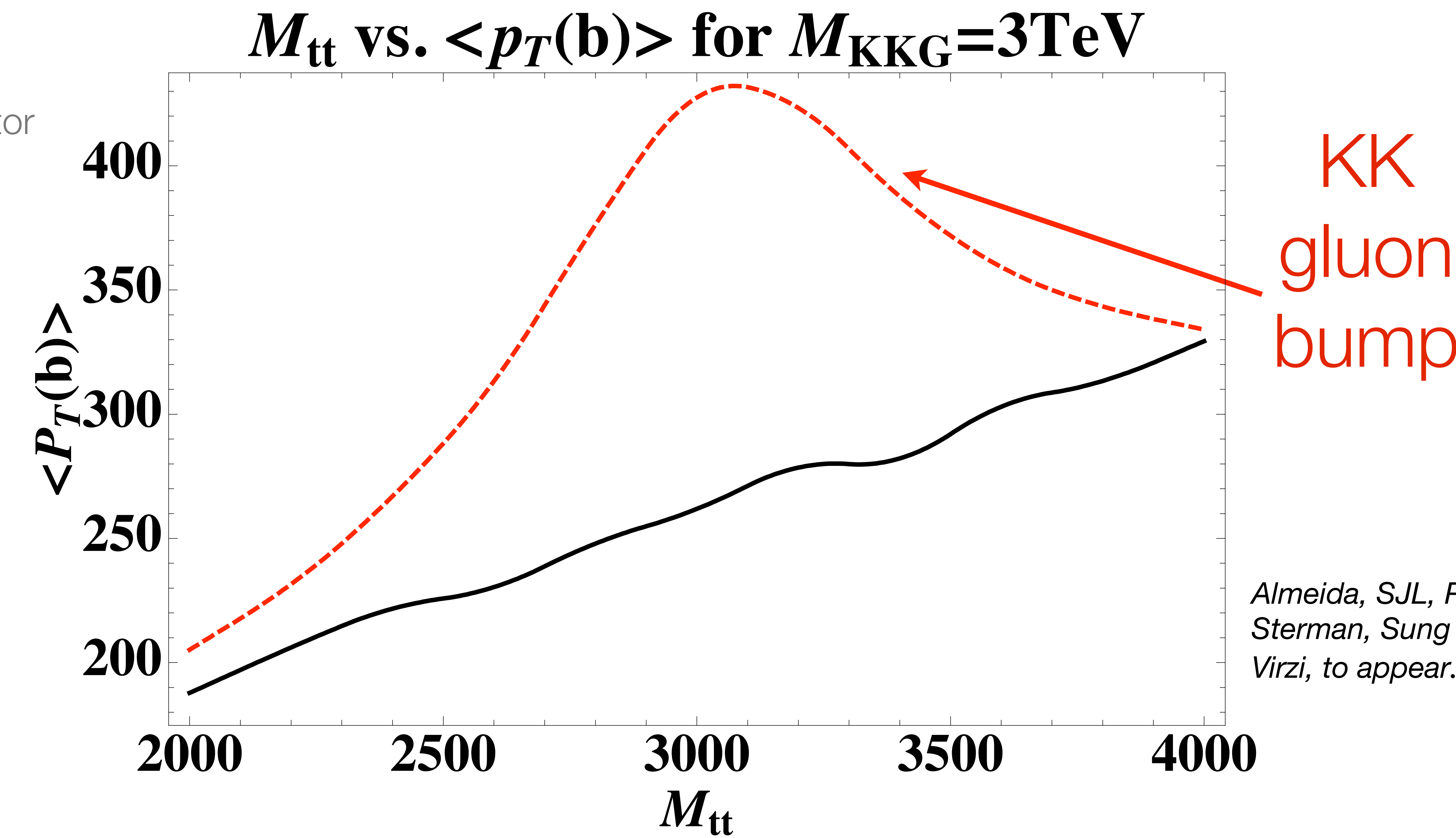


Also relevant for SUSY: heavy stop decaying into top and wino

Example: KK gluon

lepton PT is harder near the KK gluon plateau

MG/ME
Without Detector
Simulation



Almeida, SJL, Perez, Sterman, Sung & Virzi, to appear.

Also relevant for SUSY: heavy stop decaying into top and wino

Example: KK gluon

b-quark PT is harder near the KK gluon bump

Summary

- LHC => new era, precision top physics
- Theory+technique to tag t/W/Z/h jets
- Understand jet mass, but it's not enough
- Introduce Jet-shapes: very useful, but more to do (exp'+analyses+theory)

Some References for Boosted (hadronic) t/W/Z/h

- W. Skiba and David Tucker-Smith (hep-ph/0701247)
- B. Holdom (arXiv:0705.1736 [hep-ph])
- J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam (arXiv:0802.2470 [hep-ph])
- G. Brooijmans, ATLAS note, ATL-PHYS-CONF-2008-008
- J. Thaler and L. T. Wang (arXiv:0806.0023 [hep-ph])
- D. E. Kaplan, K. Rehermann, M. D. Schwartz and B. Tweedie (arXiv: 0806.0848 [hep-ph])